A Tsunami Forecast Model for Eureka, California

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Contents

Abstract

In support of the National Oceanic and Atmospheric Administration's tsunami forecast system, we have developed and tested a numerical tsunami model for the city of Eureka, California and the communities on Humboldt Bay. The Eureka tsunami forecast model employs the optimized version of the Method of Splitting Tsunami (MOST) numerical code and has been validated and tested using data from 12 historical tsunamis and a set of 43 synthetically generated mega events (forced by Mw 9.3 earthquakes). A high-resolution reference model, without limitations on computational run-times, has also been developed to provide comparison for the forecast model. Validation results show good agreement between the forecast and reference models, and also with sea level data available from the Eureka tide-gauge.

1.0 Background and Objectives

The National Oceanic and Atmospheric Administration (NOAA) Center for Tsunami, Research (NCTR) at the NOAA Pacific Marine Environmental Laboratory (PMEL) has developed a tsunami forecasting capability for operational use by NOAA's two Tsunami Warning Centers located in Hawaii and Alaska (Titov *et al.*, 2005). The system is designed to efficiently provide basin-wide warning of approaching tsunami waves accurately and quickly. The system, termed Short-term Inundation Forecast of Tsunamis (SIFT), combines real-time tsunami event data with numerical models to produce estimates of tsunami wave arrival times and amplitudes at a coastal community of interest. The SIFT system integrates several key components: deep-ocean observations of tsunamis in real time, a basin-wide pre-computed propagation database of water level and flow velocities based on potential seismic unit sources, an inversion algorithm to refine the tsunami source based on deep-ocean observations during an event, and high-resolution tsunami forecast models termed Standby Inundation Models (SIMs).

Eureka is in Humboldt County in Northern California, 270 miles north of San Francisco. The city is located on Humboldt Bay, a large deep-water bay home to both large industrial docks and numerous marinas serving fishing and recreational boats. The population of Eureka is 26,157 (2008, California Statistical Abstract). Neighboring Arcata, located on the northern edge of Humboldt Bay, has a population of 17,417. The estimated total population living in communities bordering Humboldt Bay is 80,000.

2.0 Forecast Methodology

A high-resolution inundation model was used as the basis for development of a tsunami forecast model to operationally provide an estimate of wave arrival time, wave height, and inundation in Eureka and surrounding communities following tsunami generation. All tsunami forecast models are run in real time while a tsunami is propagating across the open ocean. The Eureka model was designed and tested to perform under stringent time constraints given that time is generally the single limiting factor in saving lives and property. The goal of this work is to maximize the length of time that residents of the area have to react to a tsunami threat by providing accurate information quickly to emergency managers and other officials responsible for the community and infrastructure.

The general tsunami forecast model, based on the Method of Splitting Tsunami (MOST), is used in the tsunami inundation and forecasting system to provide real-time tsunami forecasts at selected coastal communities. The model runs in minutes while employing high-resolution grids constructed by the National Geophysical Data Center. The Method of Splitting Tsunami (MOST) is a suite of numerical simulation codes capable of simulating three processes of tsunami evolution: earthquake, transoceanic propagation, and inundation of dry land. The MOST model has been extensively tested against a number of laboratory experiments and benchmarks (Synolakis *et al.*, 2008) and was successfully used for simulations of many historical tsunami events. The main objective of a forecast model is to provide an accurate, yet rapid, estimate of wave arrival time, wave height, and inundation in the minutes following a tsunami event. Titov and González (1997) describe the technical aspects of forecast model development, stability, testing, and robustness, and Tang *et al.*, 2009 provide detailed forecast methodology

A basin-wide database of pre-computed water elevations and flow velocities for unit sources covering worldwide subduction zones has been generated to expedite forecasts (Gica *et al.*, 2008). As the tsunami wave propagates across the ocean and successively reaches tsunameter observation sites, recorded sea level is ingested into the tsunami forecast application in near real-time and incorporated into an inversion algorithm to produce an improved estimate of the tsunami source. A linear combination of the pre-computed database is then performed based on this tsunami source, now reflecting the transfer of energy to the fluid body, to produce synthetic boundary conditions of water elevation and flow velocities to initiate the forecast model computation.

Accurate forecasting of the tsunami impact on a coastal community largely relies on the accuracies of bathymetry and topography and the numerical computation. The high spatial and temporal grid resolution necessary for modeling accuracy poses a challenge in the run-time requirement for real-time forecasts. Each forecast model consists of three nested grids with increasing spatial resolution in the finest grid, and temporal resolution for simulation of wave inundation onto dry land. The forecast model utilizes the most recent bathymetry and topography available to reproduce the correct wave dynamics during the inundation computation. Forecast models, including the Eureka model, are constructed for at-risk populous coastal communities in the Pacific and Atlantic Oceans. Previous and present development of forecast models in the Pacific (Titov *et al.*, 2005; Titov, 2009; Tang *et al.*, 2008; Wei *et al.*, 2008) have validated the accuracy and efficiency of each forecast model currently implemented in the real-time tsunami forecast system. Models are tested when the opportunity arises and are used for scientific research. Tang *et al.*, 2009 provide forecast methodology details.

3.0 Model Development

The general methodology for modeling at-risk coastal communities is to develop a set of three nested grids, referred to as A, B, and C-grids, each of which becomes successively finer in resolution as they telescope into the population and economic center of the community of interest. The offshore area is covered by the largest and lowest resolution A-grid while the near-shore details are resolved within the finest scale C-grid to the point that tide gauge observations recorded during historical tsunamis are resolved within expected accuracy limits. The procedure is to begin development with large spatial extent merged bathymetric topographic grids at high resolution, and then optimize these grids by sub-sampling to coarsen the resolution and shrink the overall grid dimensions to achieve a 4 to 10 hr simulation of modeled tsunami waves within the required time period of 10 min of wall-clock time. The basis for these grids is a high-resolution digital elevation model constructed by the National Geophysical Data Center and NCTR using all available bathymetric, topographic, and shoreline data to reproduce the wave dynamics during the inundation computation for an at-risk community. For each community, data are compiled from a variety of sources to produce a digital elevation model referenced to Mean High Water in the vertical and to the World Geodetic System 1984 in the horizontal (http://ngdc.noaa.gov/mgg/inundation/tsunami/inundation.html). From these digital elevation models, a set of three high-resolution, "reference" elevation grids are constructed for development of a high-resolution reference model from which an 'optimized' model is constructed to run in an operationally specified period of time. The operationally developed model is referred to as the optimized tsunami forecast model or forecast model for brevity.

Development of an optimized tsunami forecast model for Eureka began with the spatial extent merged bathymetric/topographic grids provided by the NGDC shown in Figure 3. Grid dimension extension and additional information were updated as needed and appropriate. A significant portion of the modeled tsunami waves, typically 4 to 10 hr of modeled tsunami time, pass through the model domain without appreciable signal degradation. Error! Reference source not found. provides specific details of both reference and tsunami forecast model grids, including extents and complete input parameter information for the model runs is provided in Appendix A.

3.1 Forecast Area

Eureka and the surrounding communities on Humboldt Bay are shown in the map presented in Figure 1. Humboldt Bay is about 13 miles long and consists of Arcata Bay to the north of Eureka, the South Bay, and the central Bay area. The bay entrance is south of Eureka and is protected by jetties, making the entrance easier for boats. Eureka is situated at the center of Humboldt Bay, on the hill overlooking the thinnest part of the bay’s channels. Arcata is to the north, and other smaller unincorporated communities, such as Fairhaven, Manila, Indianola and King Salmon surround the bay. A channel from the bay entrance to north of Eureka is dredged to a depth of 35-40 feet to accommodate larger vessels docking at a number of shipping facilities on the central bay in and around Eureka. There are three islands in the Bay, all just north of Eureka: Indian Island is the largest, Woodley Island is the second and the site for a marina, and Daby Island the smallest.

There are a number of sites in the area to consider when assessing tsunami threats. There are two small air-fields in the region: the Eureka Municipal Airport is located south of Fairhaven on the spit across from Eureka; and Murray Field is just to the northeast of Eureka in the Fay Slough area. A natural gas and electric power plant is sited opposite the bay’s entrance and north of King Salmon. The main transportain artery in the region, Highway 101, borders Humboldt Bay from north to south, connecting Eureka and Arcata and the rest of California.

The Humboldt Bay National Wildlife Refuge is an important natural and tourist component of the Bay. The Refuge is mainly in the shallow and marshy South Bay, but also rings Arcata Bay.   The mudflats and eelgrass beds here provide habitat for local and migratory birds, with estimates as high as 100,000 birds being present. The Bay is also important for spawning and feeding fish.

3.2 Tide gauge data

NOAA's National Ocean Service operates a tide gauge sensor at North Spit in Humboldt Bay. The gauge is located on the dock at the Humboldt Bay Coast Guard Station, at 40 46′ N and 124 13.0 W. The dock is near the bay entrance on the inshore side of spit, across the bay and south of Eureka. The tide gauge was established in August of 1977. The mean tidal range at the gauge location is 4.89 feet. An image of the tide gauge shack on the CG pier is shown in Figure 4, and the location of the tide gauge is shown in the maps in Figure 5 and Figure 6, denoted by the red star.

Before comparing the tide gauge data to the model predicted wave heights it must be de-tided and smoothed. First, a running mean filter with a width of 1 hour is constructed and used to eliminate outlier points with greater than 6 standard deviations difference between the smoothed and original time series. Then the tidal and instrument noise are eliminated using a band-pass digital Fourier filter with cutoffs at the high and low frequency ends of 8 minutes and 3 hours. The resulting observed sea surface height changes due to historical tsunamis are used to compare and validate our modeled time-series predictions of those events.

3.3 Model Setup

The grids developed for the reference and forecast models were derived from the Pacific basin-wide 30 arc-second grid developed at NCTR (#REF#), and the 1/3 arc-second DEM developed by NGDC (#REF). The Eureka DEM is shown in Figure 3. The grid extents and parameters of the forecast and reference model grids are detailed in table 1. The forecast and reference grid sets were set up using the same boundaries. The A-grid covers the United States coast from central California in the south to central Oregon in the north, and out to the deep ocean to the west. The B-grid focuses on the region surrounding Humboldt Bay. It was designed to cover the bathymetry and topography of Point Mendocino to the south of Humboldt and Patrick's

Point to the north. The highest resolution C-grid zooms in on Humboldt Bay itself, with its goal to describe the waves and water levels of the Bay and along the coastal spits.

The developed reference and forecast model grids are shown in Figure 5 and Figure 6, respectively.

4.0 Results and Discussion

4.1 Model Validation

We use twelve historical tsunamis to validate and test the Eureka forecast and reference models. The locations, magnitudes, and unit source combinations used to describe these events are described in Table 1. The events selected for testing range from smaller to larger originating earthquakes (7.7 to 9.2 M_W), and are from varied locations around the Pacific Rim. The majority of the events are more recent since we have higher quality descriptions of the earthquakes and can describe the tsunamagenic response more accurately. The locations and magnitudes of the eleven historical events are plotted in Figure 7.

Results and comparisons from the forecast and reference models for the historical events are shown in Figures 8 - 19. In each figure the top two axes show the maximum amplitude for the forecast and reference models, respectively, and the lower axis shows the time series of wave amplitude from both models at the location of the Eureka tide gauge. Data from the tide gauge is also plotted on this axis when available for the event. Note that the color scale and axes limits change from figure to figure.

The first tsunami event used for validation is the 1946 Unimak 8.5 M_W earthquake. The forecast and reference model results are shown in Figure 8. Both models show similar wave heights offshore, with the main difference being the location of the wave cusps. Heights inside the harbor are also well matched except for the bay opposite the jetty entrance. The time-series of wave amplitude at the tide gauge shows that the forecast model predictions match the reference model well at that location.

The model responses to the 1960 Chilean tsunami are shown in Figure 9. Wave heights of almost a meter are predicted on the ocean side of the Humboldt Bay spits, while in the Bay the maximum height is less – about 0.75 meters. Both the forecast and reference models predict inundation in the South Bay and along the slough north of Eureka. The tide gauge time series shows that the forecast model is doing a good job of resolving the tsunami response.

The 1964 Alaskan earthquake, with a magnitude of 9.3 M_W, caused damage and deaths in Alaska, Oregon and California. In Figure 10 the predicted wave heights are shown and are seen to match well (note that the color scale has been allowed to wash out the ocean maxima so that the details inside the Bay are apparent). Inside the Bay, maxima are 2.6 and 2.7 meters for the forecast and reference models, respectively. Observations from the event of waterlines on docks and structures estimated maximum run-up of 2.1 meters. The models both predict inundation at many locations around the bay, including in Eureka itself. The time series at the tide gauge shows the models predicting similar waves, with magnitudes of 1.3 meters.

The next four events used for validation are all moderate events that did not have much impact on Eureka. The 1994 Kuril earthquake is predicted to cause offshore waves on the order of 20 centimeters (Figure 11), while inside the bay the highest values are approximately 14 cms. Both the maximum height maps and the tide-gauge time series match well. For both the 1996 Andreanof (Figure 12) and 2003 Rat Island (Figure 13) earthquakes we have real tide-gauge data but the resulting tsunami at Eureka is small enough that the wave height signal is not very easily separated from the noise level. For Andreanof, the predicted wave heights are less than 10 cms at all points in the C-grid, while for the Rat Island event there are no values greater than 7 cms.

Figure 14 shows the predictions for the 2006 Tonga event and the forecast and reference models agree well, showing maxima of approximately 20 cms south of the jetty on the ocean side and no significant waves inside the harbor.

The Kuril events of 2006 and 2007 are shown in Figures 15 and 16, respectively. The 2006 tsunami led to a larger wave-height signal at Eureka, and this is reflected in the plots. The tide gauge data for the 2006 event is plotted in the lower panel of Figure 15 and the models predict values that are comparable. The 2007 Kuril tsunami is smaller with a smaller area of ocean maxima. For both events the forecast model does well in reproducing the reference model wave-height prediction.

The Salomon tsunami of 2007 (Figure 17) is interesting because, although it results in a small tsunami with maximum wave heights of less than 10 cms, the wave heights inside the harbor are comparable to the ocean values. Both the forecast and reference models show ~8 cm heights in the Bay north of the entrance and east of Eureka itself.

The last historical event used here for model validation is the one caused by the Chilean earthquake of 2010, which caused major destruction and over 500 deaths. The forecast and reference models predict similar wave-height maxima, with waves of over 30 cms on the ocean side of the spits. Inside the harbor, the reference model shows higher wave-heights, possibly due to an instability that develops in the channel entrance. The forecast model does not reproduce this instability. The tide-gauge at Eureka measured wave peaks between 10 and 20 cms. The forecast and reference models reproduce the time-series at the tide-gauge very well – predicting quality estimates of both amplitude and phase. It should be noted though, that the modeled time series are delayed by 11 minutes to give a better correlation. This temporal offset for this Chile 2010 event has been observed in testing at other sites and the cause is under investigation. Lastly, note that there is no significant inundation for this strong event.

4.2 Model stability testing using synthetic scenarios

To further test the stability and robustness of the forecast model, we use a set of 43 synthetic mega-tsunamis. These events are 'synthetic' in the sense that they do not represent actual historical earthquakes, but allow us the flexibility to stress test our model using large forcing inputs from many different directions. These Mw 9.3 synthetic events each use a set of 20 unit sources, corresponding to a rupture area of 1000 km by 100 km, and are located all around the Pacific Basin and in each subduction zone. For comparison, the 2004 Indian Ocean tsunami that resulted in hundreds of thousands of deaths in Indonesia, and was detectable globally was the result of a Mw 9.1 earthquake. Table 3 describes the synthetic events used and their unit source combinations and Figure 20 shows the locations of these events and their positions relative to Eureka.

The resulting time series of wave amplitude at the Eureka tide gauge location as predicted from the forecast model are shown in Figure 21 - 23. The largest signal seen from these events is due to the ACSZ07 event, whose source is on the Juan de Fuca fault and is the closet event used for testing. The event is close enough that there is local deformation causing the initial wave height to be over 6 meters high. The highest signals from the far field come from the ACSZ04 event, resulting in over 2 meter high waves at the Eureka tide gauge. This event source is in the Gulf of Alaska, centered near Kodiak Island. Surveying the rest of the synthetic event plots, there are some generalizations to be made. The Central and South America sources (CSSZ) don't cause strong wave height response at Eureka, most likely due to the direction of wave energy from these areas. Mega events from sources in the Kamchatka-Kuril-Japan-Izu-Mariana-Yap zone (KISZ) lead to significant waves at Eureka, with the KISZ05 causing 2 meter waves at the tide gauge. Events originating from the Eastern Philippines (EPSZ), Manus-Oceanic Convergent Boundary (MOSZ) and New Guinea (NGSZ) subduction zones lead to moderate waves at Eureka.

It should be noted that the wave heights discussed in the previous plots are what the forecast model predicts at the location of the Eureka tide gauge. As we've seen from the historical events presented earlier, the Eureka tide gauge is located in a spot that will usually have lower waves than other spots in Humboldt Bay. For reference we should look at the maximum wave heights predicted for these synthetic mega-events.

Figure 24 shows the maximum wave height predicted on the forecast model C-grid for the ACSZ04 synthetic event. Wave heights of 10 meters are seen along the ocean side of the north and south spits. The south spit is completely overrun by waves and the north spit shows inundation in most locations. Inside the harbor there is inundation in the low marshy areas in the South Bay and north in Arcata Bay, but more importantly, also at King Salmon and the south-western edges of Eureka. The KISZ05 mega-event (Figure 25) shows similar inundation patterns but with lower heights and less inundation, specifically on the south spit and the slough area of southeast Arcata Bay.

5.0 Summary and Conclusions

We have developed a set of optimized and reference tsunami forecast models for Eureka and Humboldt Bay. The models have been validated using historical tsunamis events and stress-tested using synthetic mega-tsunami events. For historical events where tide gauge data is available, the model predictions compared favorably at the tide gauge location. The grid developed for the forecast model has resolutions in longitude and latitude of 2.0 and 1.6 arc-seconds – corresponding to a grid spacing of ~47 meters. Four hours of model time can be run in under 10 minutes, providing fast wave height estimates.

The models give accurate predictions of wave height and water velocity in response to tsunami forcing. These models are part of NOAA's tsunami forecast and warning system and we be used to predict in real-time the potential threat of tsunami waves for the people and resources of the communities on Humboldt Bay.

Tables

Table 1: MOST setup parameters for reference and forecast models for Eureka, California.

Grid	Region	Reference Model: Coverage Lat. [ºN] Lon. [ºE]	Reference Model: Cell Size ["]	Reference Model: nx x ny	Reference Model: Time Step [sec]	Forecast Model: Coverage Lat. [º N] Lon. [ºE]	Forecast Model: Cell Size ["]	Forecast Model: nx x ny	Forecast Model: Time Step [sec]
A	US West Coast	38.5 – 44.0 233.2 – 236.8	36 x 36	361 x 551	2.7	38.5 – 44.0 233.2 – 236.8	144 x 72	236 x 251	8.0
B	Northern California	40.3 – 41.3 235.3 – 235.95	6 x 6	391 x 601	0.9	40.4 – 41.3 235.4 – 235.93	24 x 18	331 x 153	3.2
C	Humboldt Bay	40.67– 40.87 235.71 – 235.92	0.5 x 0.5	1513 x 1441	0.3	40.67– 40.87 235.71 – 235.92	2.0 x 1.6	367 x 178	1.6
Minimum offshore depth [m]		5				5			
Water depth for dry land [m]		0.1				0.1			
Friction coefficient [n^2]		0.0009				0.0009			
CPU time for 4-hr simulation		11.6 hr				9.8 min			

Computations were performed on a single Intel Xeon processor at 3.6 GHz, Dell PowerEdge 1850.

Earthquake / Seismic				Mode	
Event	USGS Date Time (UTC) Epicenter	CMT Date Time (UTC) Centroid	Magnitude Mw	Tsunami Magnitude[1]	Subduction Zone
1946 Unimak	01 Apr 12:28:56 52.75ºN 163.50ºW	01 Apr 12:28:56 53.32ºN 163.19ºW	[2]8.5	8.5	Aleutian-Alaska-Cascadia (ACSZ
1960 Chile	22 Apr 19:11:17 39.50ºS 74.50ºW		[3]9.2		Central-South America (CSSZ)
1964 Alaska	28 Mar 03:36:00 [3]61.02ºN 147.65ºW	28 Mar 03:36:14 61.10ºN 147.50ºW	[3]9.2	9.0	Aleutian-Alaska-Cascadia (ACSZ
1994 East Kuril	04 Oct 13:22:58 43.73ºN 147.321ºE	04 Oct 13:23:28.5 43.60ºN 147.63ºE	[5]8.3	8.1	Kamchatka-Kuril-Japan-Izu-Mariana- (KISZ)
1996 Andreanov	10 Jun 04:03:35 51.56ºN 175.39ºW	10 Jun 04:04:03.4 51.10ºN 177.410ºW	[5]7.9	7.8	Aleutian-Alaska-Cascadia (ACSZ
2003 Rat Island	17 Nov 06:43:07 51.13ºN 178.74ºE	17 Nov 06:43:31.0 51.14ºN 177.86ºE	[5]7.7	7.8	Aleutian-Alaska-Cascadia (ACSZ
2006 Tonga	03 May 15:26:39 20.13ºS 174.161ºW	03 May 15:27:03.7 20.39ºS 173.47ºW	[5]8.0	8.0	New Zealand-Kermadec-Tonga (NT
2006 Kuril	15 Nov 11:14:16 46.607ºN 153.230ºE	15 Nov 11:15:08 46.71ºN 154.33ºE	[5]8.3	8.1	Kamchatka-Kuril-Japan-Izu-Mariana- (KISZ)
2007 Kuril	13 Jan 04:23:20 46.272ºN 154.455ºE	13 Jan 04:23:48.1 46.17ºN 154.80ºE	[5]8.1	7.9	Kamchatka-Kuril-Japan-Izu-Mariana- (KISZ)
2007 Solomon	01 Apr 20:39:56 8.481ºS 156.978ºE	01 Apr 20:40:38.9 7.76ºS 156.34ºE	[3]8.1	8.2	New Britain-Solomons-Vanuatu (NV
2009 Samoa	29 Sep 17:48:10 15.509ºS 172.034ºW	29 Sep 17:48:26.8 15.13ºS 171.97ºW	[5]8.1	8.1	New Zealand-Kermadec-Tonga (NT
2010 Chile	27 Feb 06:34:14 35.909ºS 72.733ºW	27 Feb 06:35:15.4 35.95ºS 73.15ºW	[5]8.8	8.8	Central-South America (CSSZ)

[1] Preliminary source – derived from source and deep-ocean observations
[2] López and Okal (2006)
[3] United States Geological Survey (USGS)

Table 2 Historical events used for validation of the Eureka, California model.

Name of Scenario	Unit Source Combination	Name of Scenario	Unit Source Combination
ACSZ 1	A1-A10, B1-B10	NTSZ 4	A30-A39, B30-B39
ACSZ 2	A11-A20, B11-B20	NVSZ 1	A1-A10, B1-B10
ACSZ 3	A21-A30, B21-B30	NVSZ 2	A11-A20, B11-B20
ACSZ 4	A31-A40, B31-B40	NVSZ 3	A21-A30, B21-B30
ACSZ 5	A41-A50, B41-B50	NVSZ 4	A28-A37, B28-B37
ACSZ 6	A46-A55, B46-B55	MOSZ 1	A1-A10, B1-B10
ACSZ 7	A56-A65, B56-B65	MOSZ 2	A8-A17, B8-B17
CSSZ 1	A1-A10, B1-B10	NGSZ 1	A1-A10, B1-B10
CSSZ 2	A11-A20, B11-B20	NGSZ 2	A6-A15, B6-B15
CSSZ 3	A21-A30, B21-B30	EPSZ 1	A1-A10, B1-B10
CSSZ 4	A31-A40, B31-B40	EPSZ 2	A9-A18, B9-B18
CSSZ 5	A41-A50, B41-B50	RNSZ 1	A1-A10, B1-B10
CSSZ 6	A51-A60, B51-B60	RNSZ 2	A13-A22, B13-B22
CSSZ 7	A61-A70, B61-B70	KISZ 1	A1-A10, B1-B10
CSSZ 8	A71-A80, B71-B80	KISZ 2	A11-A20, B11-B20
CSSZ 9	A81-A90, B81-B90	KISZ 3	A21-A30, B21-B30
CSSZ 10	A91-A100, B91-B100	KISZ 4	A32-A41, B32-B41
CSSZ 11	A101-A110, B101-B110	KISZ 5	A42-A51, B42-B51
CSSZ 12	A106-A115, B106-B115	KISZ 6	A52-A61, B52-B61
NTSZ 1	A1-A10, B1-B10	KISZ 7	A56-A65, B56-B65
NTSZ 2	A11-A20, B11-B20	KISZ 8	A66-A75, B66-B75
NTSZ 3	A21-A30, B21-B30		

Table 3 Unit source combinations used to generate synthetic mega-tsunami scenarios for robustness and stability testing of the Eureka forecast model.

Figures

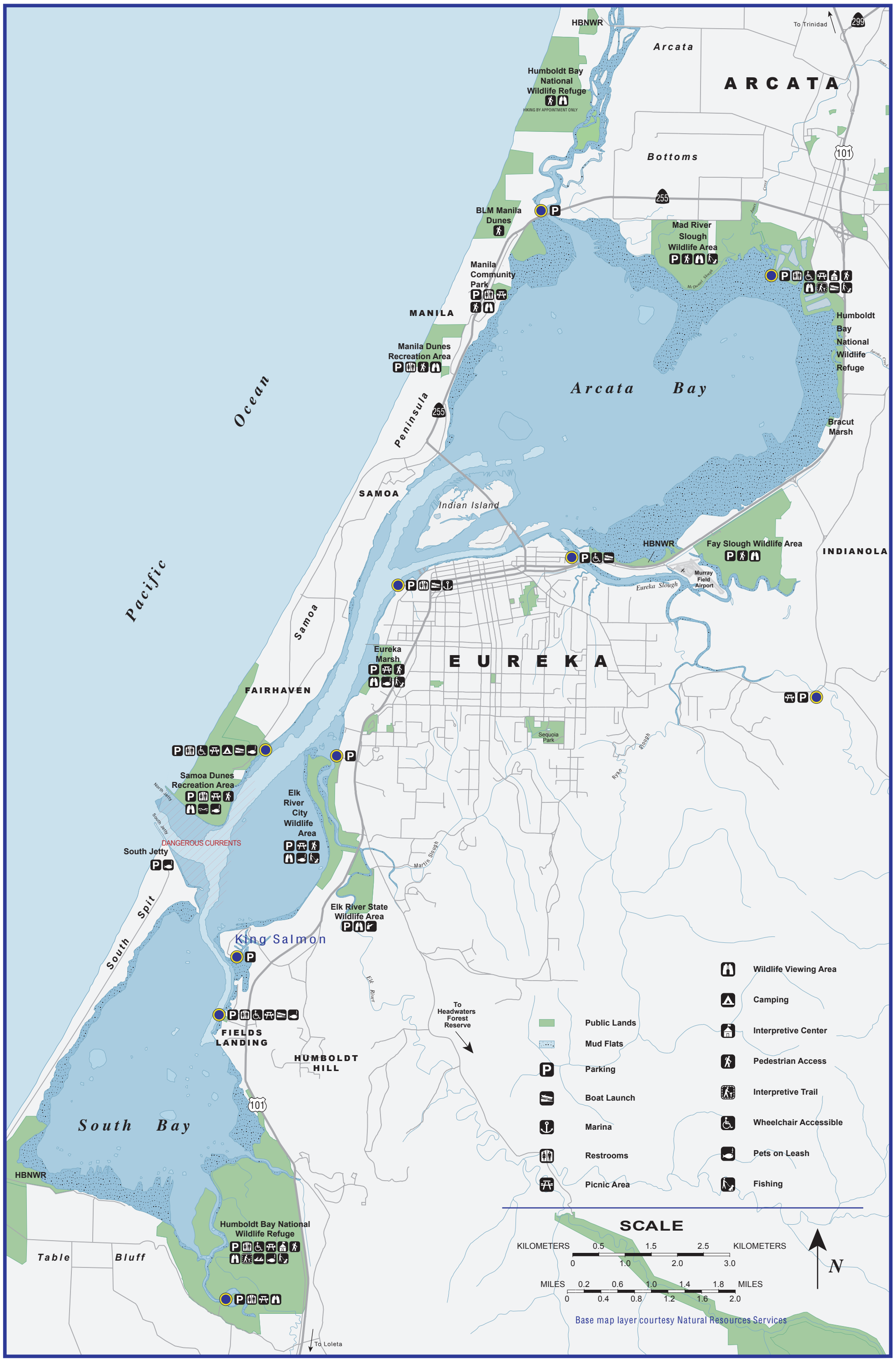

Figure 1 Map of the Eureka area. *(Courtesy of the North Coast Sea Kayakers Assoc.)*

Figure 2 An aerial photo of Eureka and Humboldt Bay. Arcata Bay is in the upper left corner and the north part of South Bay is to the right. Eureka is in the upper left quadrant of the photo. The smaller community of King Salmon is in the center-right, opposite of the bay entrance.

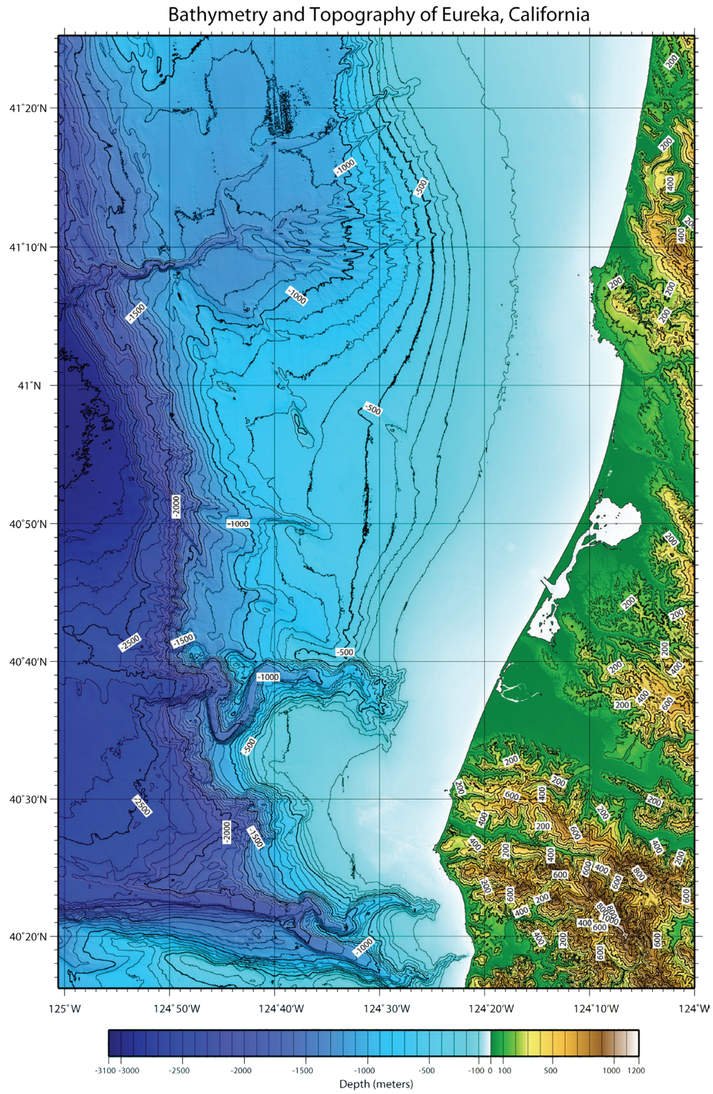

Figure 3 Shaded-relief image of the Eureka DEM. Bathymetric and topographic contour intervals are 100 meters. (Courtesy of NGDC)

Figure 4 Image of the Eureka tide gauge shack, on the pier at the Humboldt Bay Coast Guard Station.

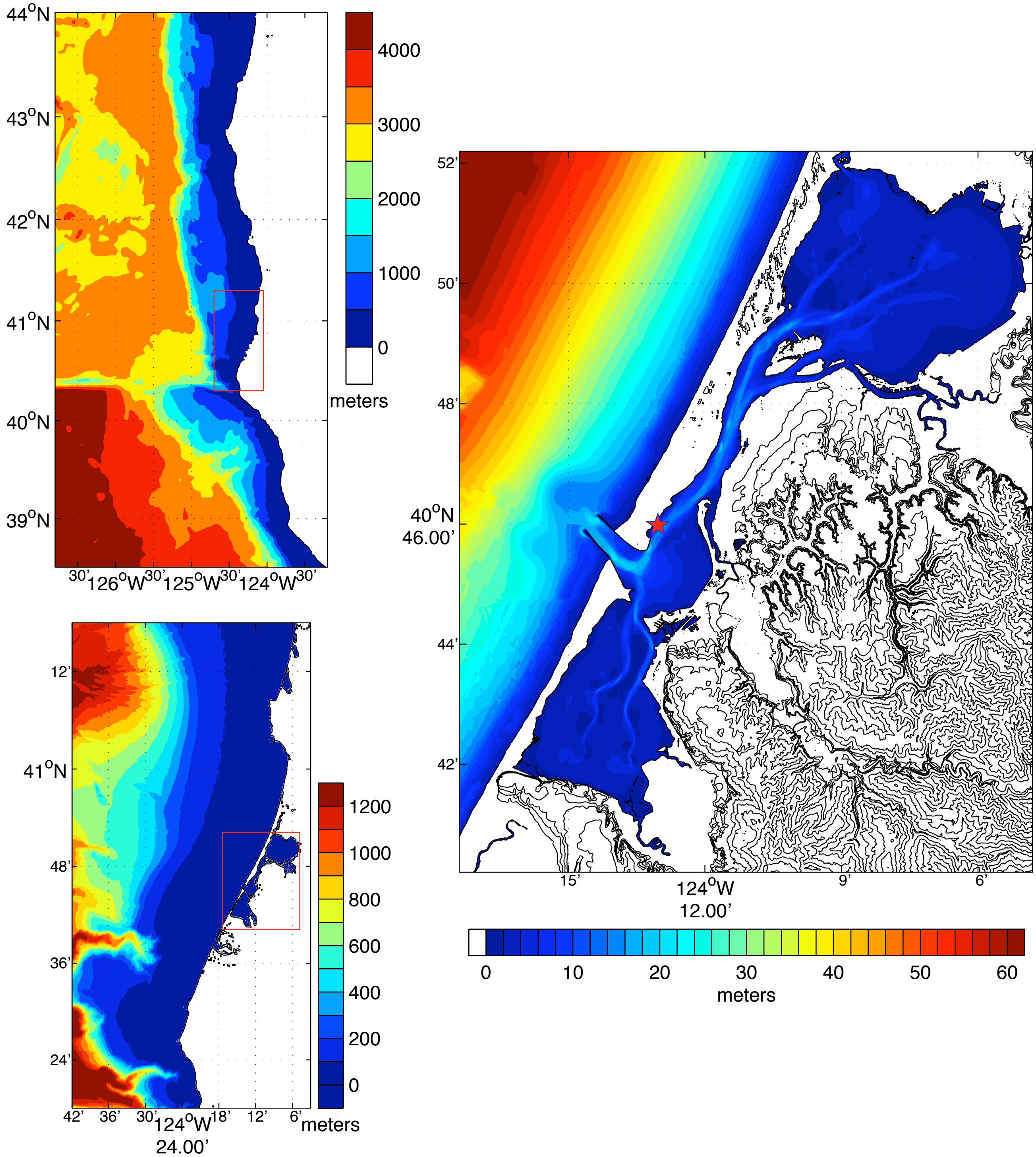

Figure 5 Bathymetry (meters) for the reference inundation model grids. The A grid is shown in the top left panel, the B grid in the bottom left panel, and the C grid in the right panel. The topography of the C grid is shown using contours with 10 meter intervals from 0 to 40 and then 40 meters intervals for higher values. The red boxes in

the A and B plots show the position of the nested B and C grids, respectively. The red star shows the location of the Eureka tide gauge installation.

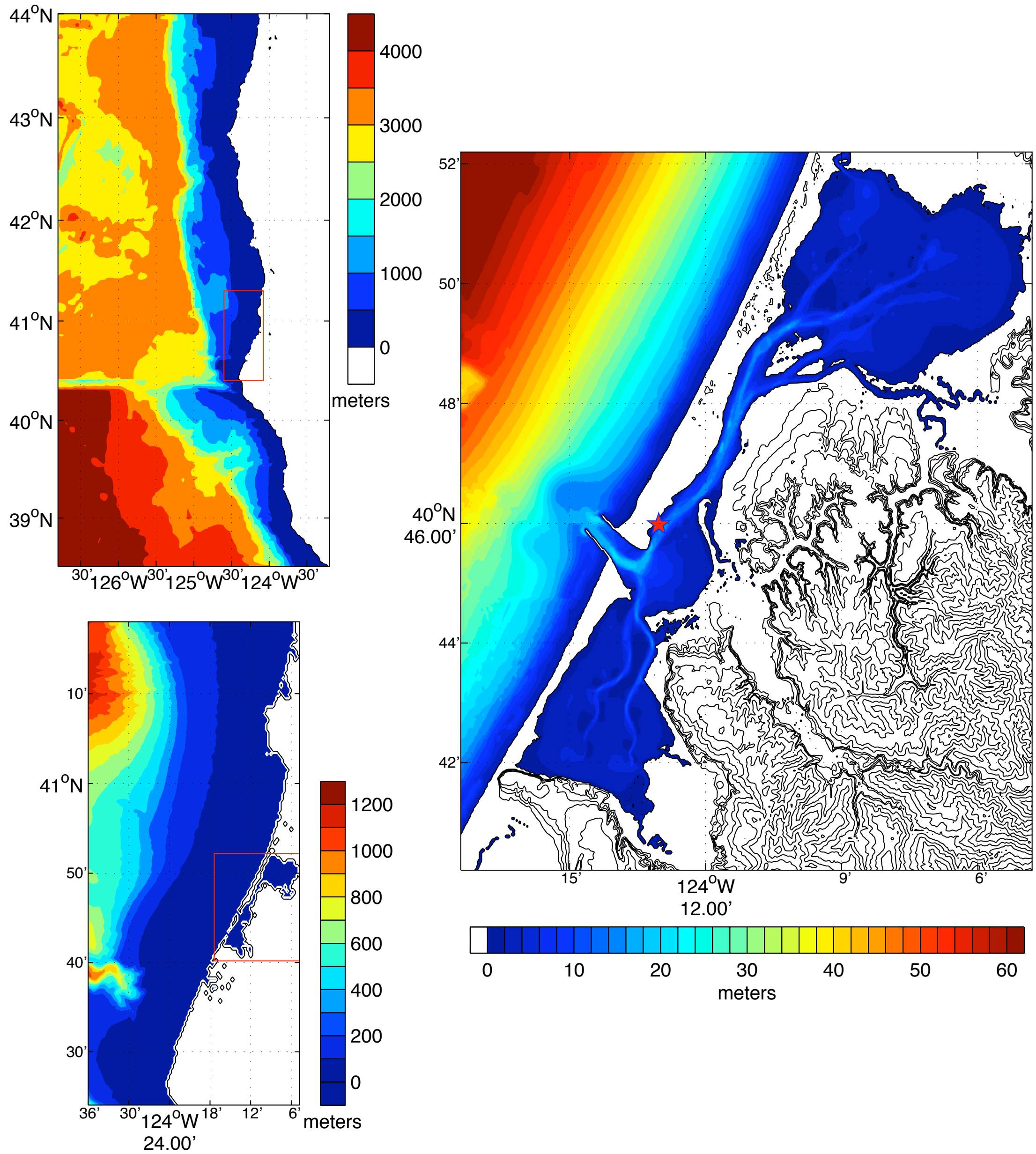

Figure 6 Bathymetry (meters) for the forecast inundation model grids. The A grid is shown in the top left panel, the B grid in the bottom left panel, and the C grid in the right panel. The topography of the C grid is shown using contours with 10 meter intervals from 0 to 40 and then 40 meters intervals for higher values. The red boxes in the A and B plots show the position of the nested B and C grids, respectively. The red star shows the location of the Eureka tide gauge installation.

Figure 7 Map of the Pacific Ocean Basin showing the locations and magnitudes of the 12 historical events used to test and validate the Eureka model. Relative earthquake magnitude is shown by the varying sizes and colors of the filled circles. The largest magnitude earthquake used in model validation was the 1964 Alaska Mw 9.2 earthquake. The star denotes Eureka's location.

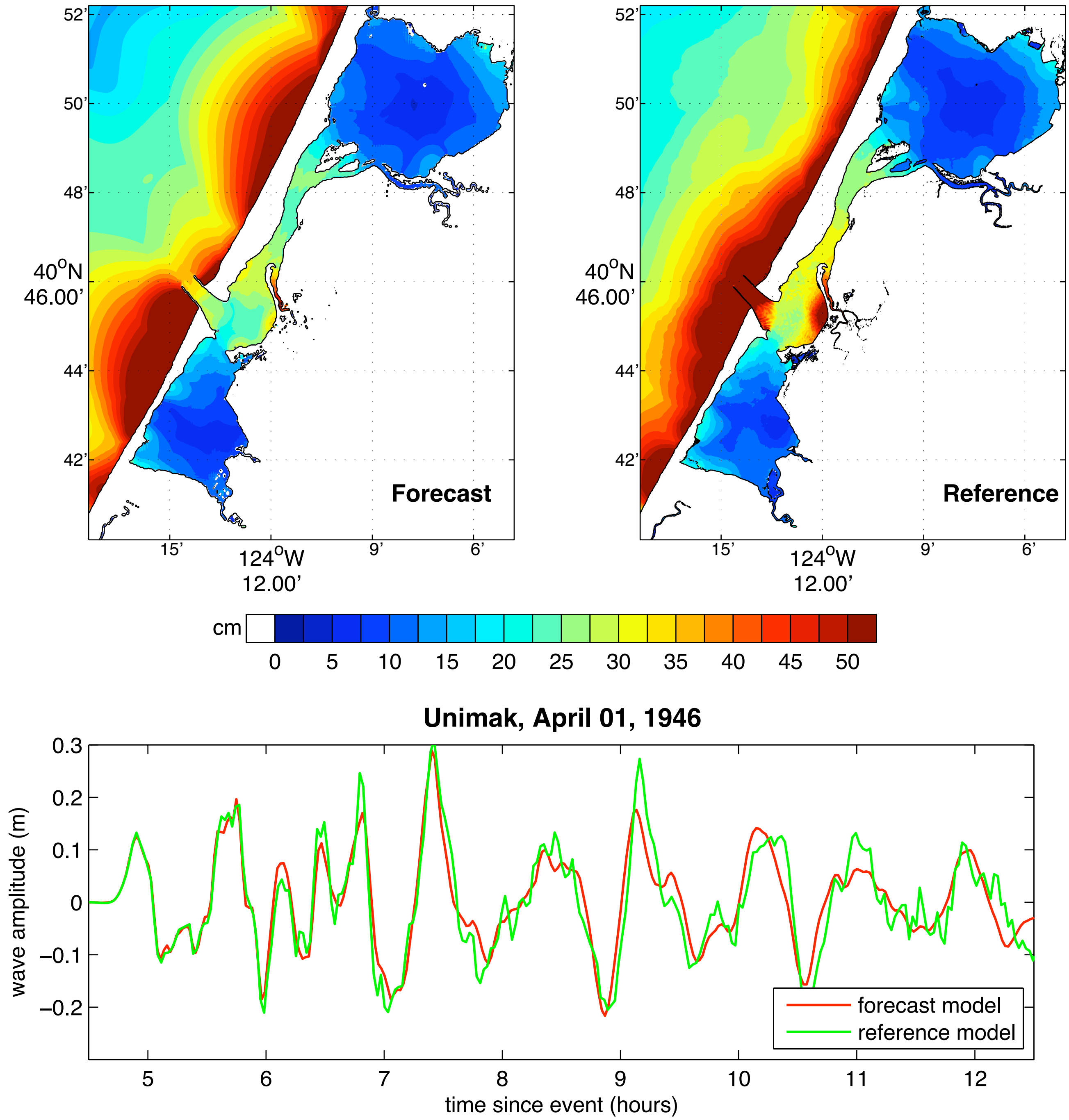

Figure 8 Model results for the 1946 Unimak Mw 8.5 event. The upper two panels show, respectively, the forecast and reference model maximum wave height predictions. The lower panel shows the forecast model (red) and reference model (green) wave amplitudes at the Eureka tide gauge.

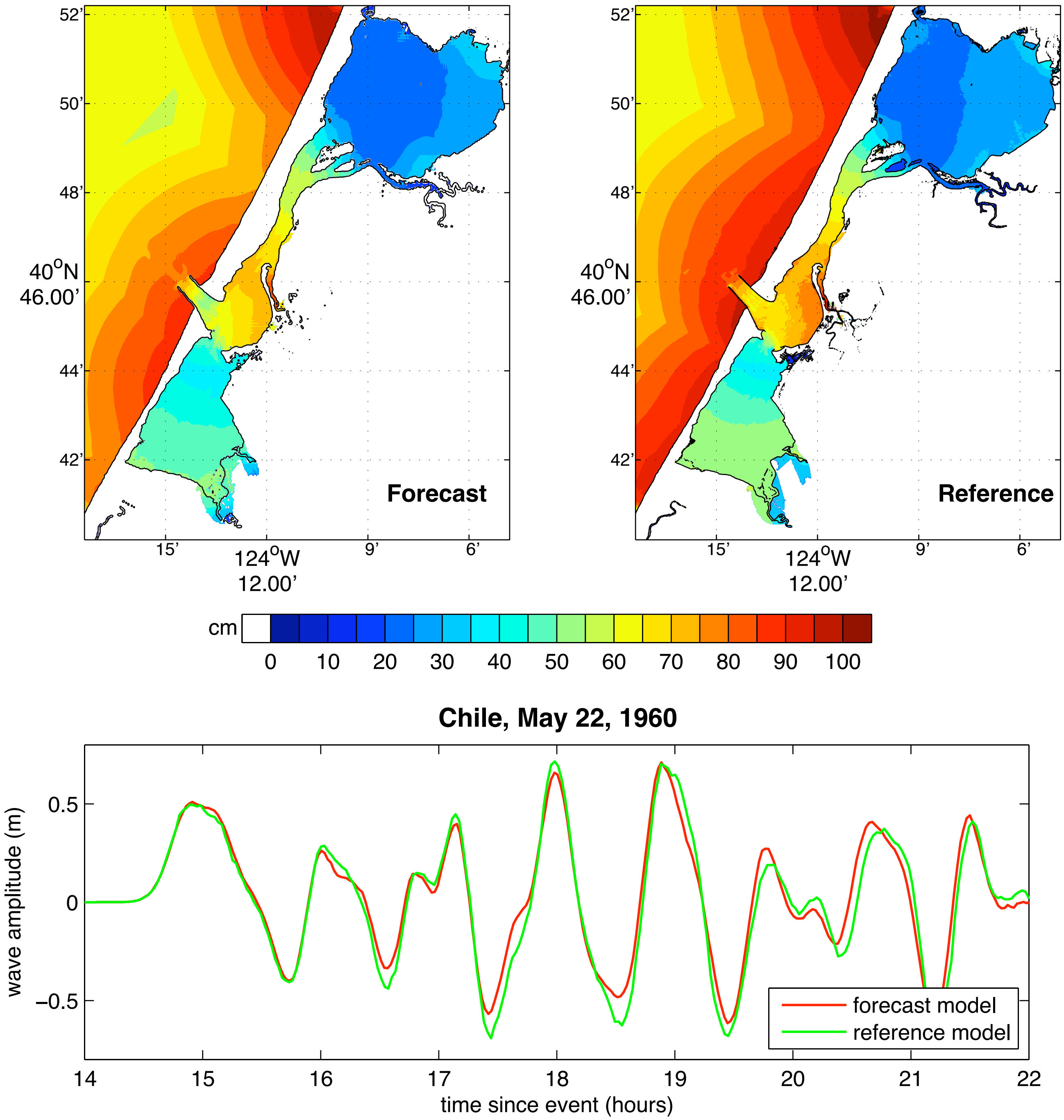

Figure 9 Model results results for the 1960 Chile Mw 9.2 event. The upper two panels show, respectively, the forecast and reference model maximum wave height predictions. The lower panel shows the forecast model (red) and reference model (green) wave amplitudes at the Shemya tide gauge

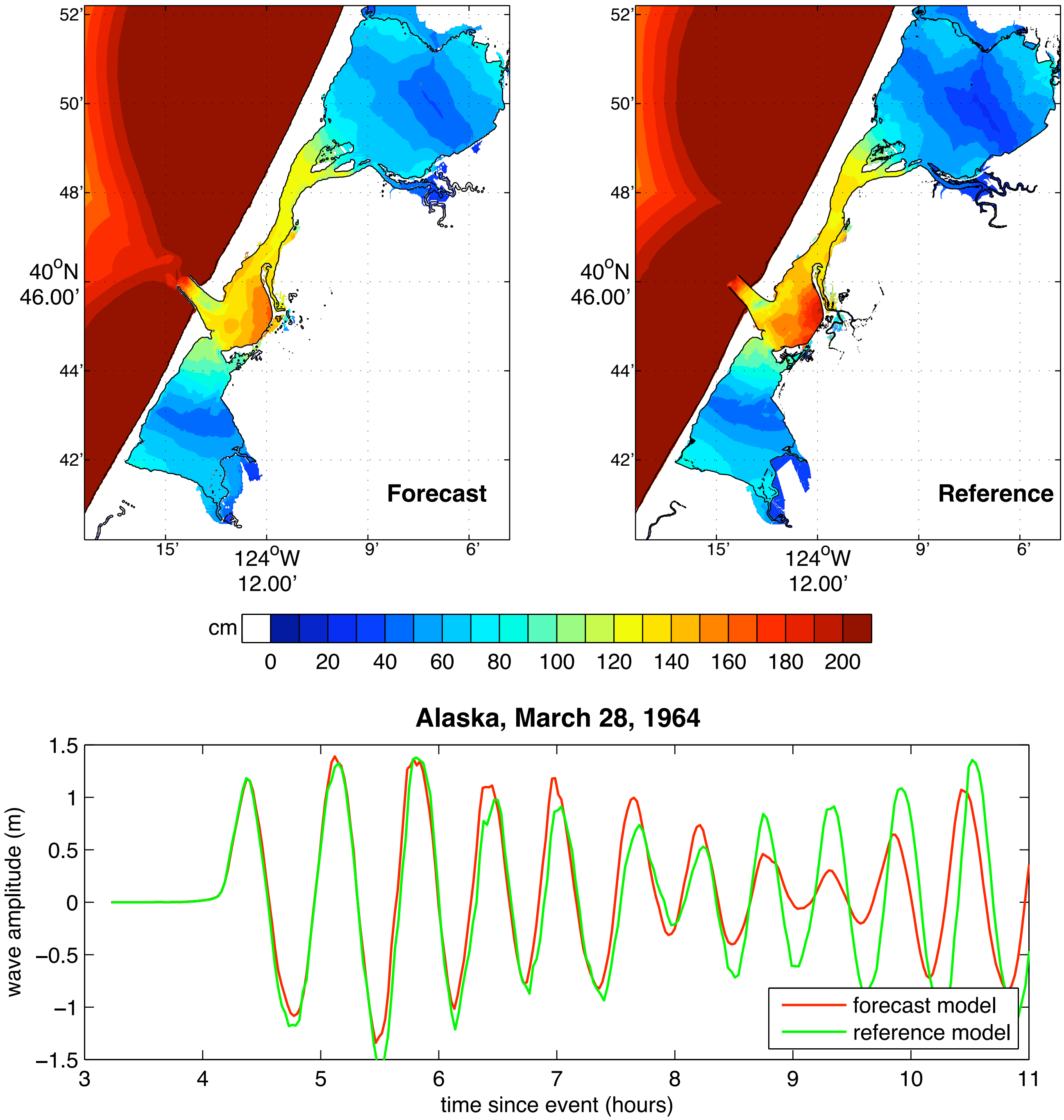

Figure 10 Model results for the 1964 Alaska Mw 9.2 event. The upper two panels show, respectively, the forecast and reference model maximum wave height predictions. The lower panel shows the forecast model (red) and reference model (green) wave amplitudes at the Shemya tide gauge

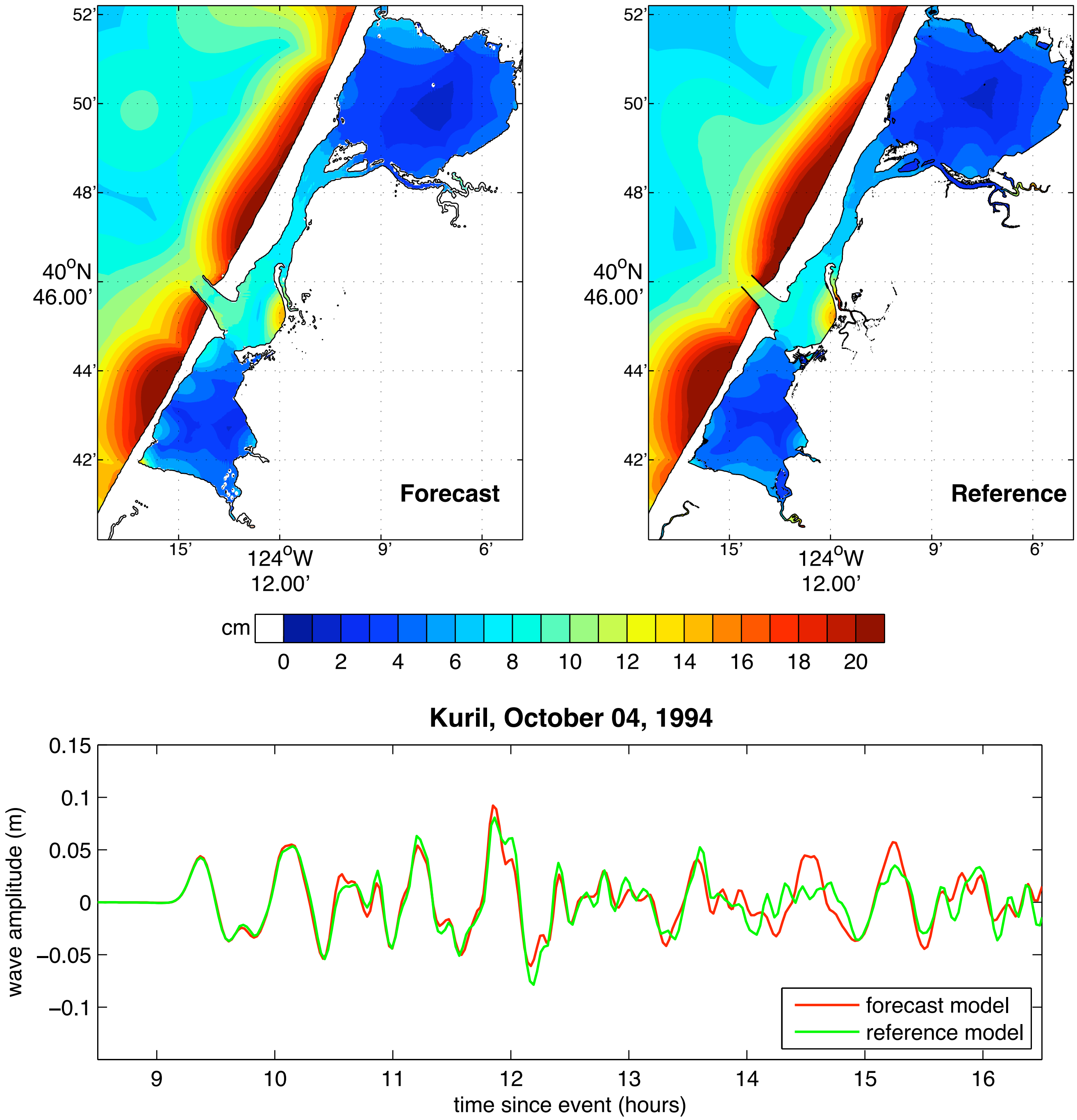

Figure 11 Model results for the 1994 Kuril Mw 8.3 event. The upper two panels show, respectively, the forecast and reference model maximum wave height predictions. The lower panel shows the forecast model (red) and reference model (green) wave amplitudes at the Shemya tide gauge.

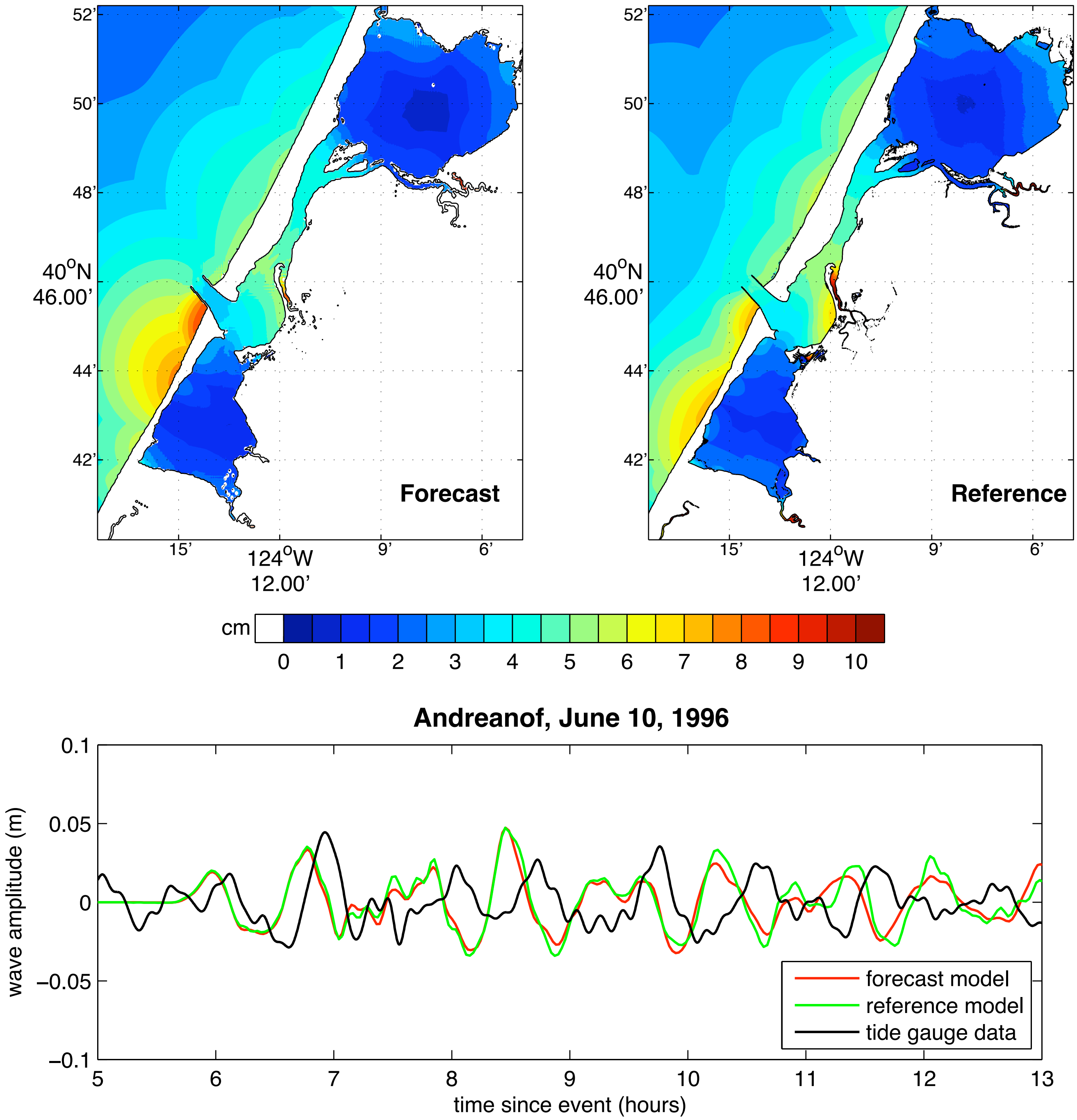

Figure 12 Model results for the 1996 Andreanof Mw 7.9 event. The upper two panels show, respectively, the forecast and reference model maximum wave height predictions. The lower panel shows the forecast model (red) and reference model (green) wave amplitudes at the Shemya tide gauge.

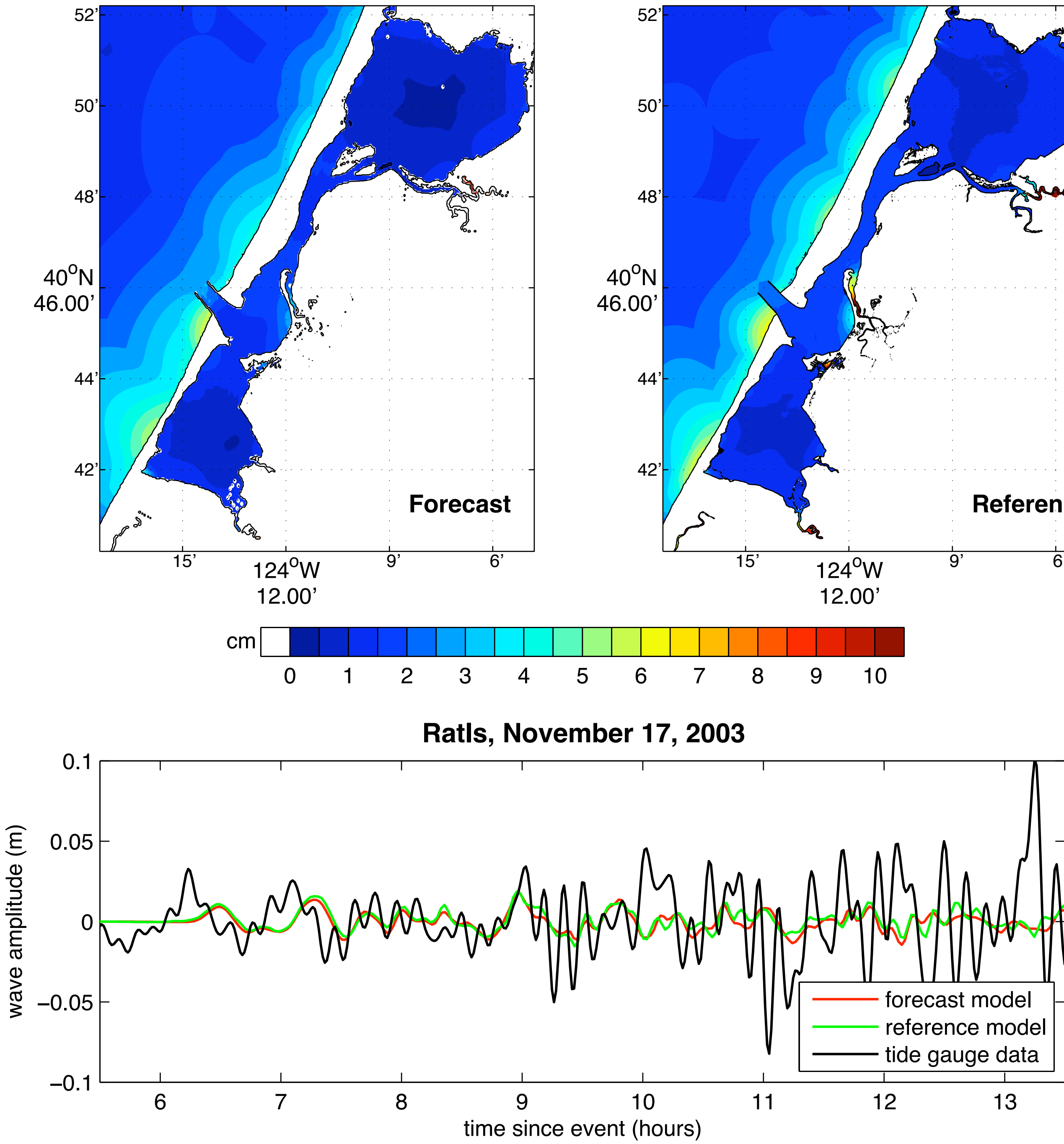

Figure 13 Model results for the 2003 Rat Island Mw 7.7 event. The upper two panels show, respectively, the forecast and reference model maximum wave height predictions. The lower panel shows the forecast model (red) and reference model (green) wave amplitudes at the Shemya tide gauge.

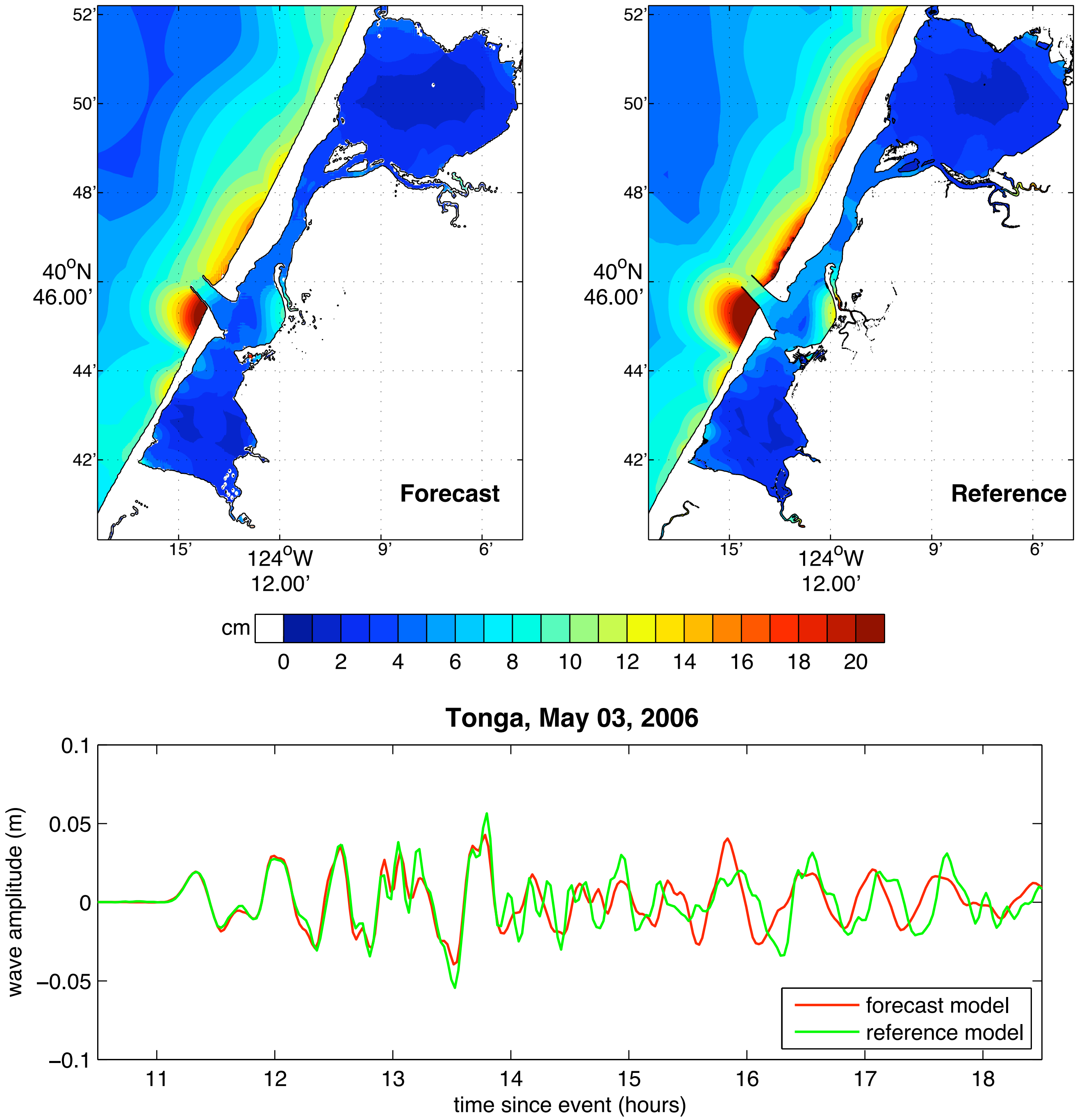

Figure 14 Model results for the 2006 Tonga Mw 8.0 event. The upper two panels show, respectively, the forecast and reference model maximum wave height predictions. The lower panel shows the forecast model (red) and reference model (green) wave amplitudes at the Shemya tide gauge.

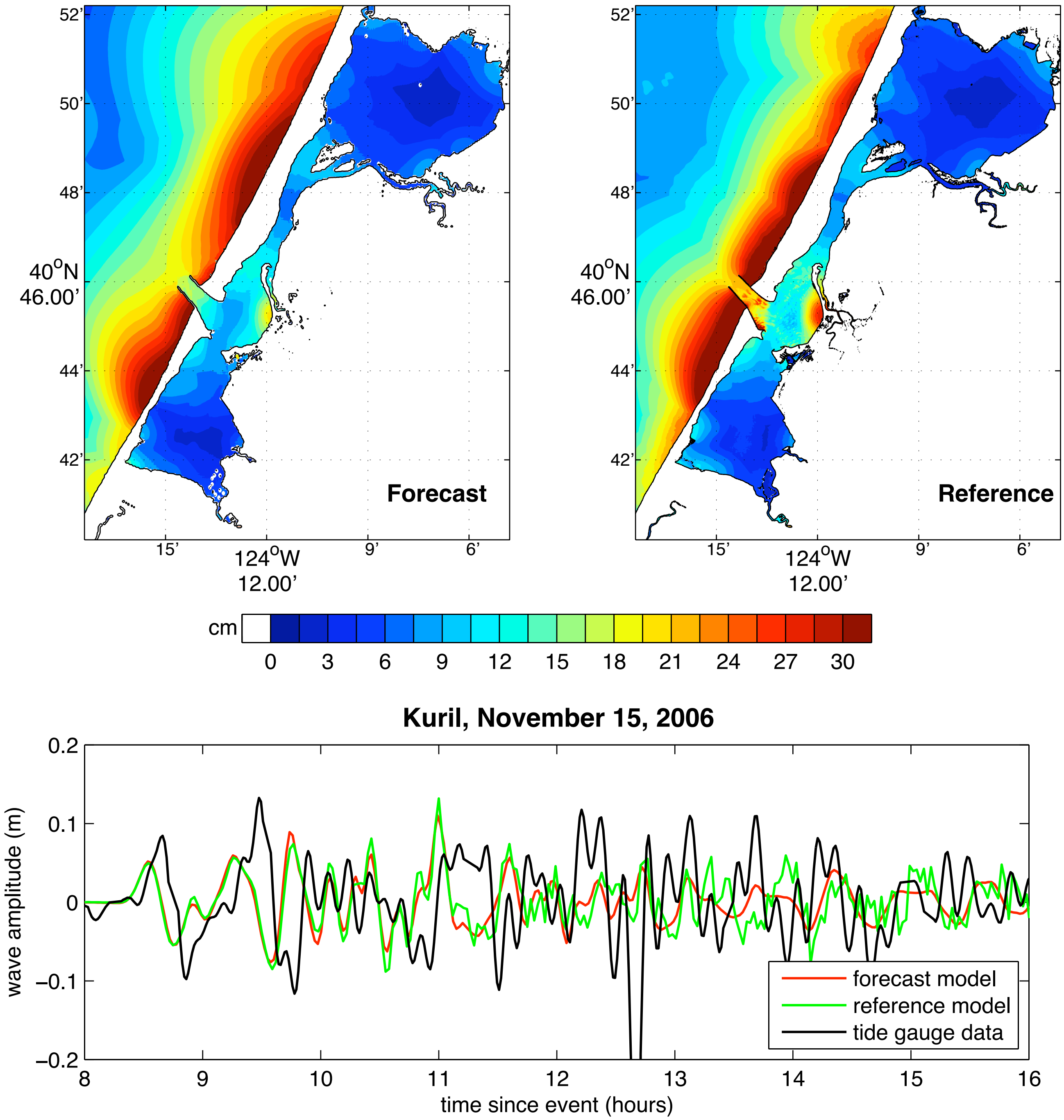

Figure 15 Model results for the 2006 Kuril Mw 8.3 event. The upper two panels show, respectively, the forecast and reference model maximum wave height predictions. The lower panel shows the forecast model (red) and reference model (green) wave amplitudes at the Eureka tide gauge.

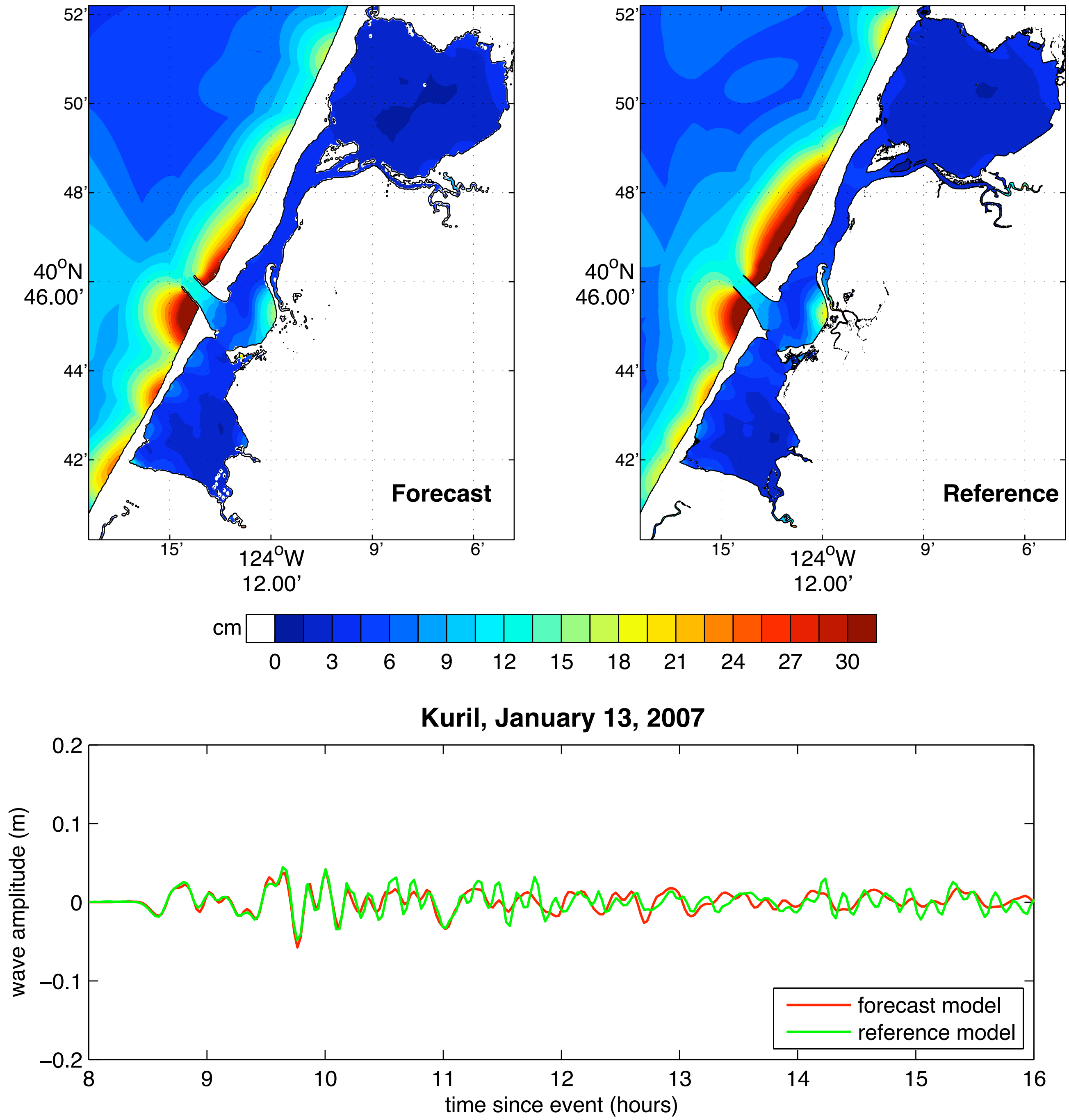

Figure 16 Model results for the 2007 Kuril Mw 8.1 event. The upper two panels show, respectively, the forecast and reference model maximum wave height predictions. The lower panel shows the forecast model (red) and reference model (green) wave amplitudes at the Eureka tide gauge.

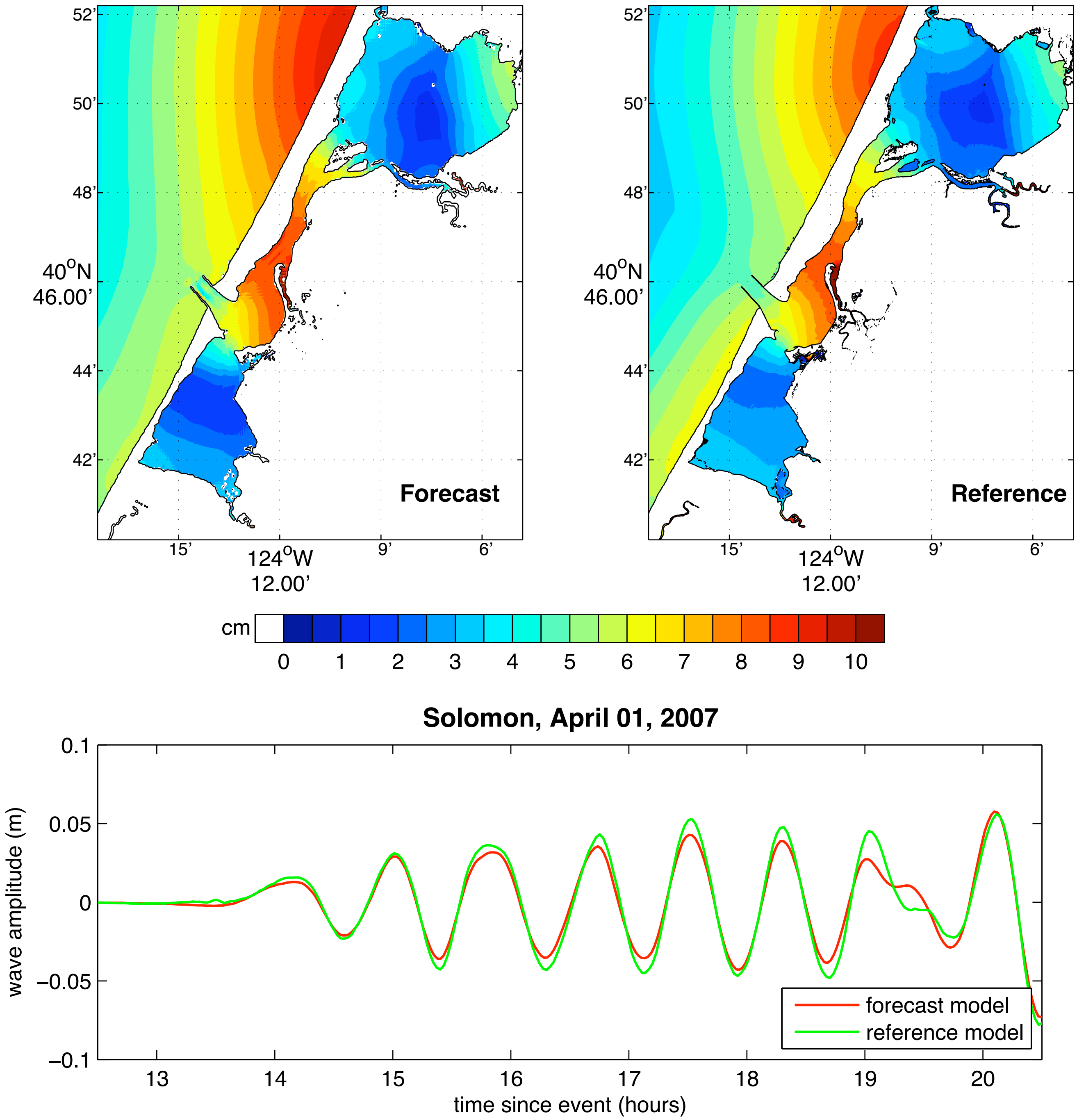

Figure 17 Model results for the 2007 Solomon Mw 8.1 event. The upper two panels show, respectively, the forecast and reference model maximum wave height predictions. The lower panel shows the forecast model (red) and reference model (green) wave amplitudes at the Eureka tide gauge.

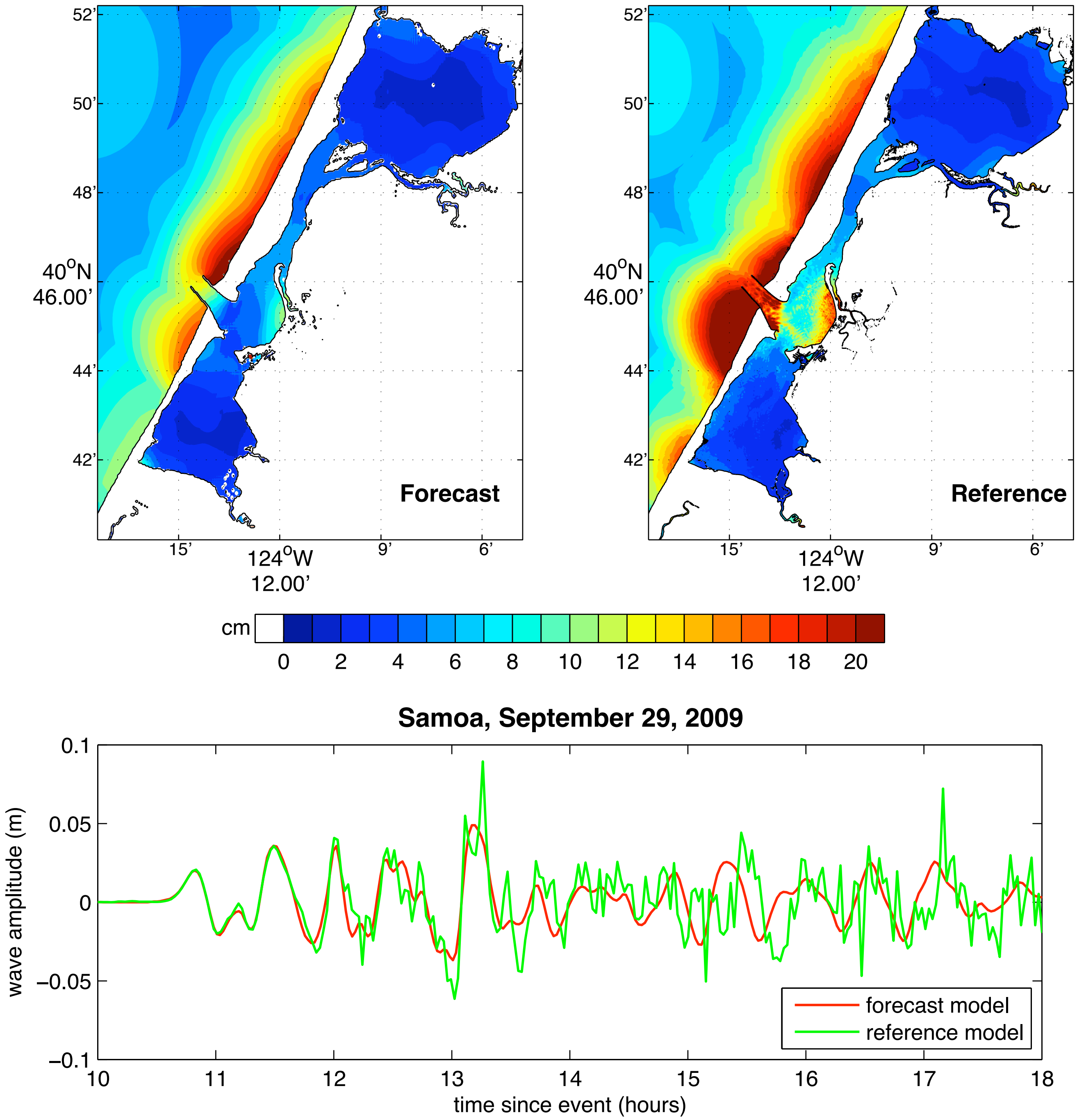

Figure 18 Model results for the 2009 Samoa Mw 8.0 event. The upper two panels show, respectively, the forecast and reference model maximum wave height predictions. The lower panel shows the forecast model (red) and reference model (green) wave amplitudes at the Eureka tide gauge.

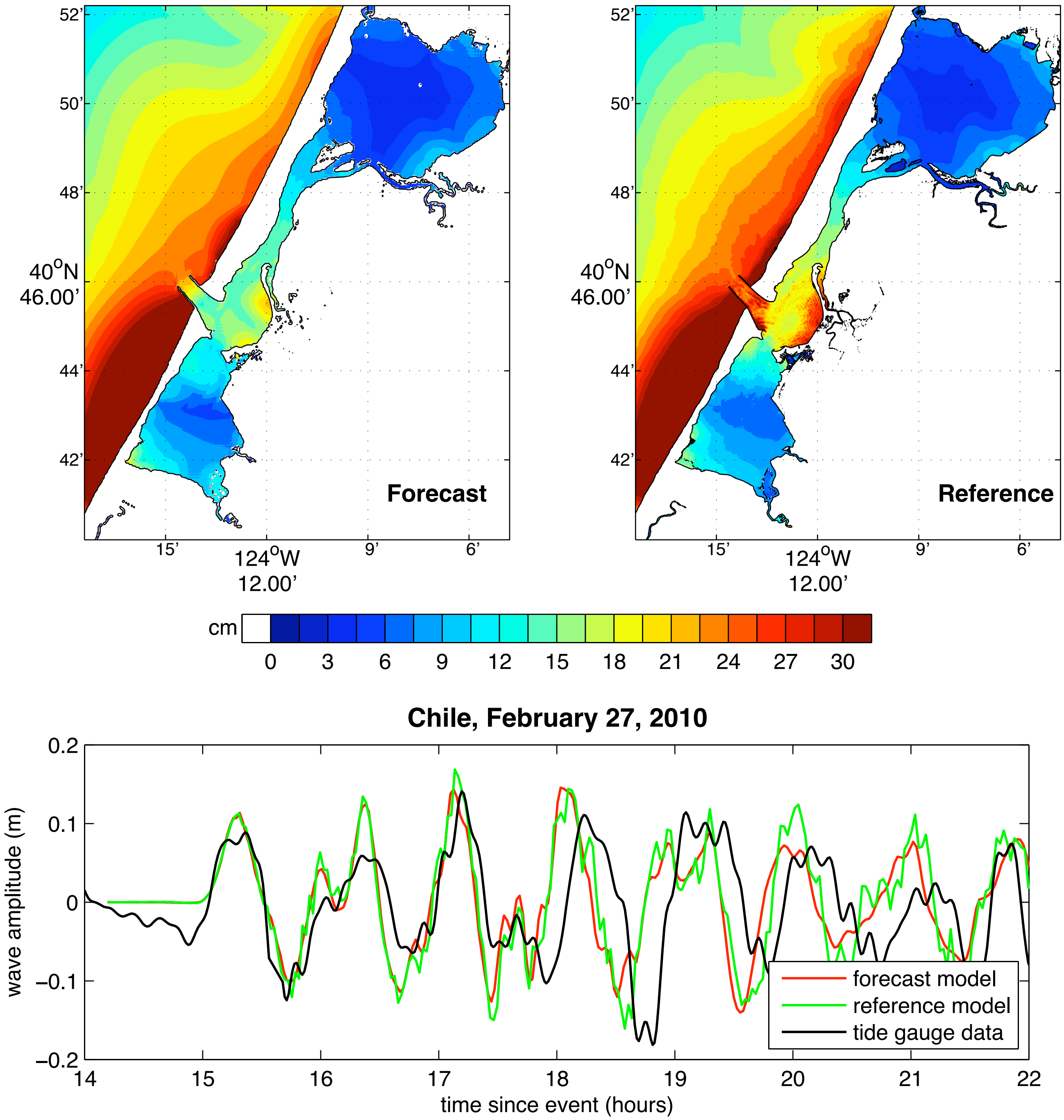

Figure 19 Model results for the 2010 Chile Mw 8.8 event. The upper two panels show, respectively, the forecast and reference model maximum wave height predictions. The lower panel shows the forecast model (red), reference model (green) and observed (black) wave amplitudes at the Eureka tide gauge.

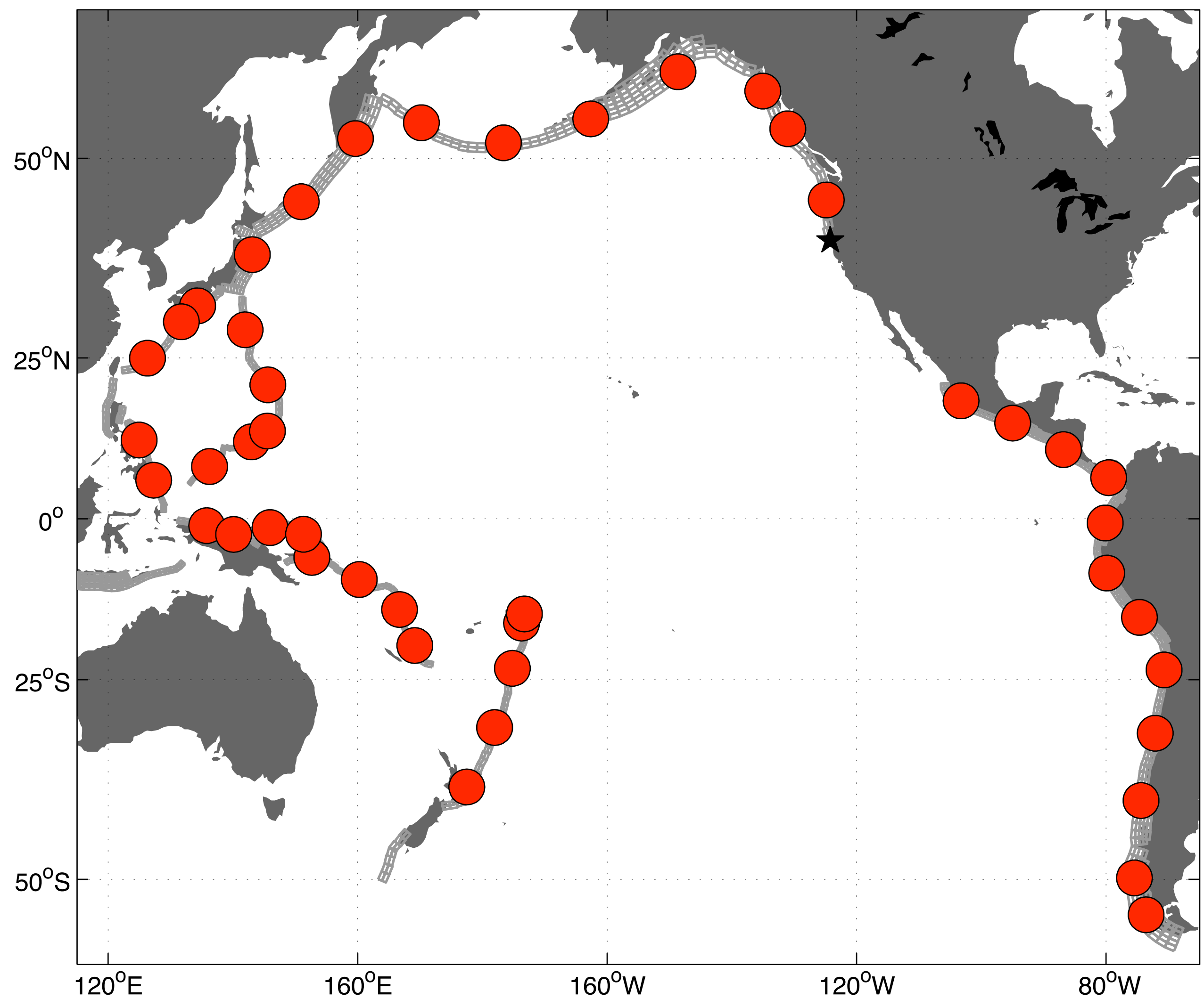

Figure 20 Map of the Pacific Ocean Basin showing the locations of the 43 simulated Mw 9.3 events used to test and validate the Eureka model. The solid star denotes the location of Eureka.

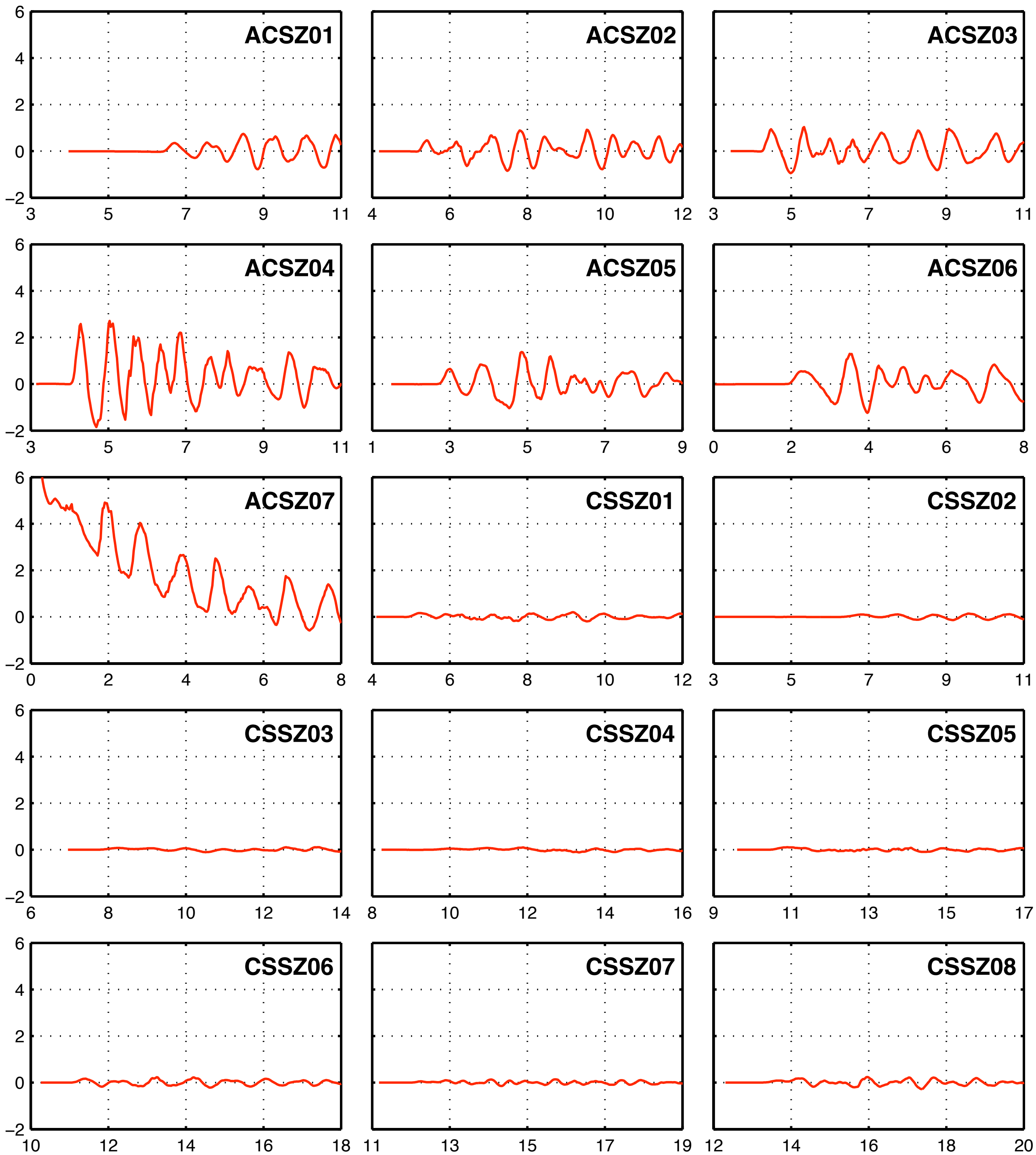

Figure 21 Wave amplitudes (in meters) from the forecast model at the location of the Eureka tide gauge for 43 simulated mega-tsunami events.

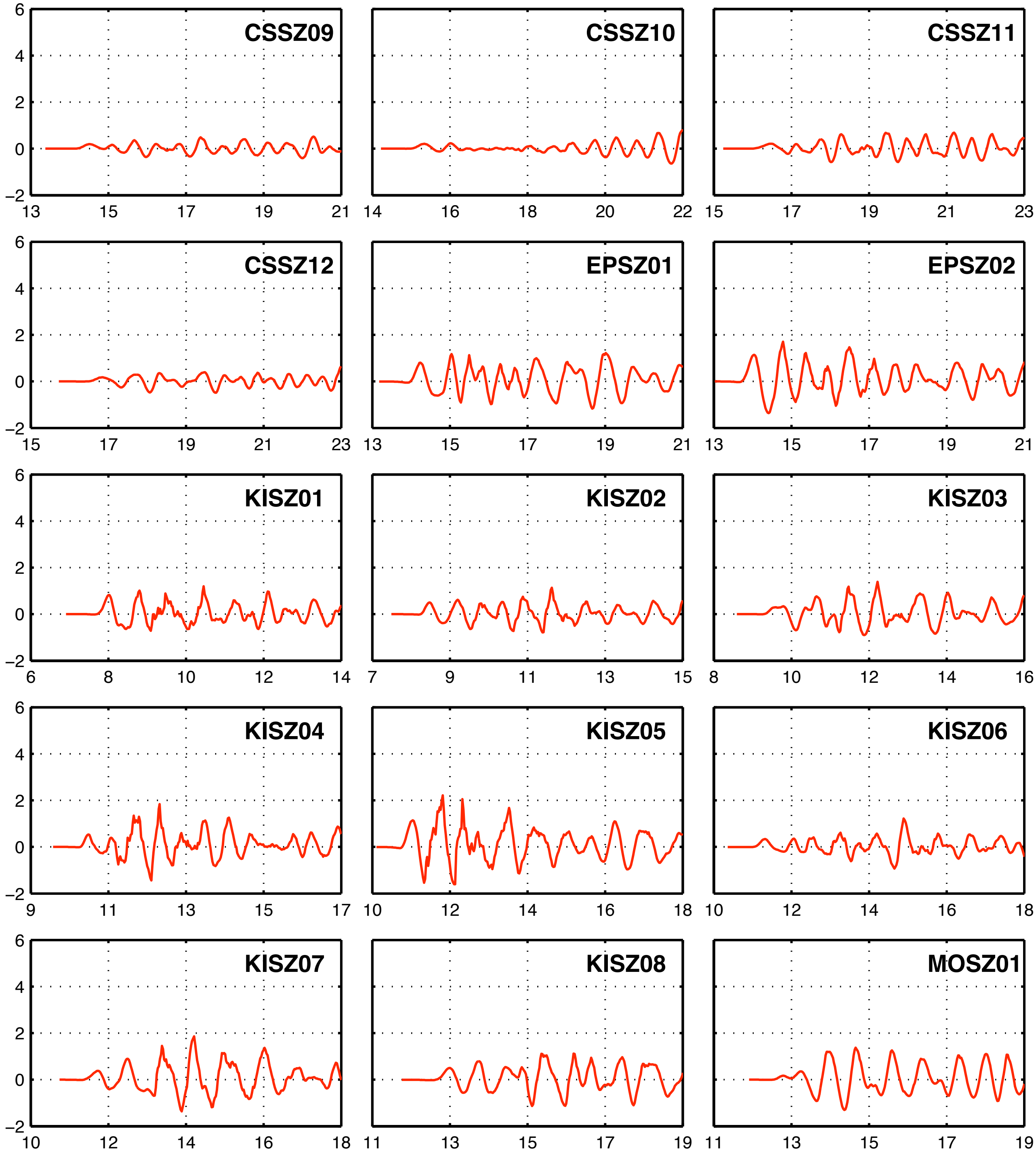

Figure 22 Continued

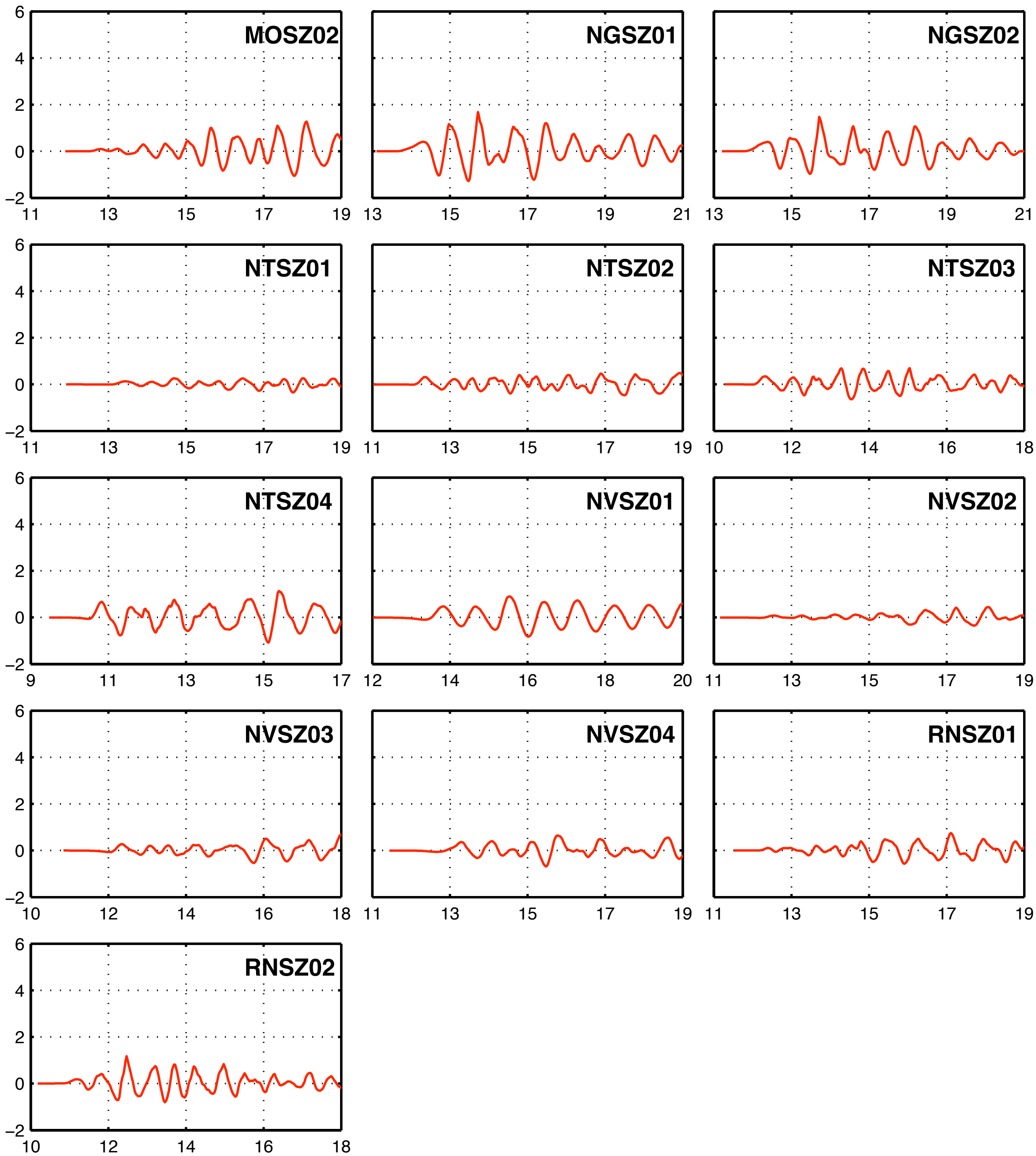

Figure 23 Continued.

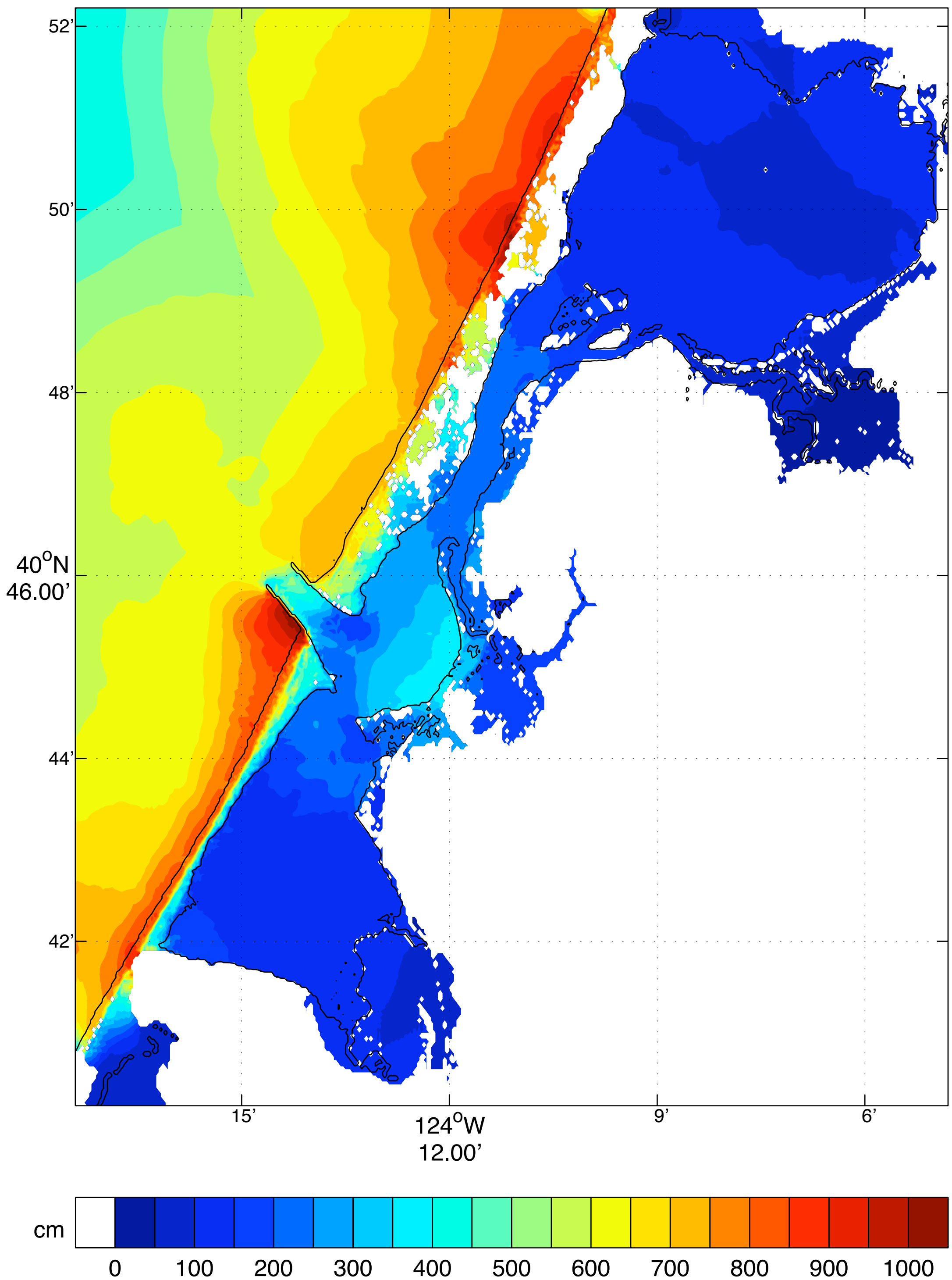

Figure 24 Map of the maximum wave height prediction from the Eureka forecast model for the ACSZ04 Mw 9.3 synthetic event.

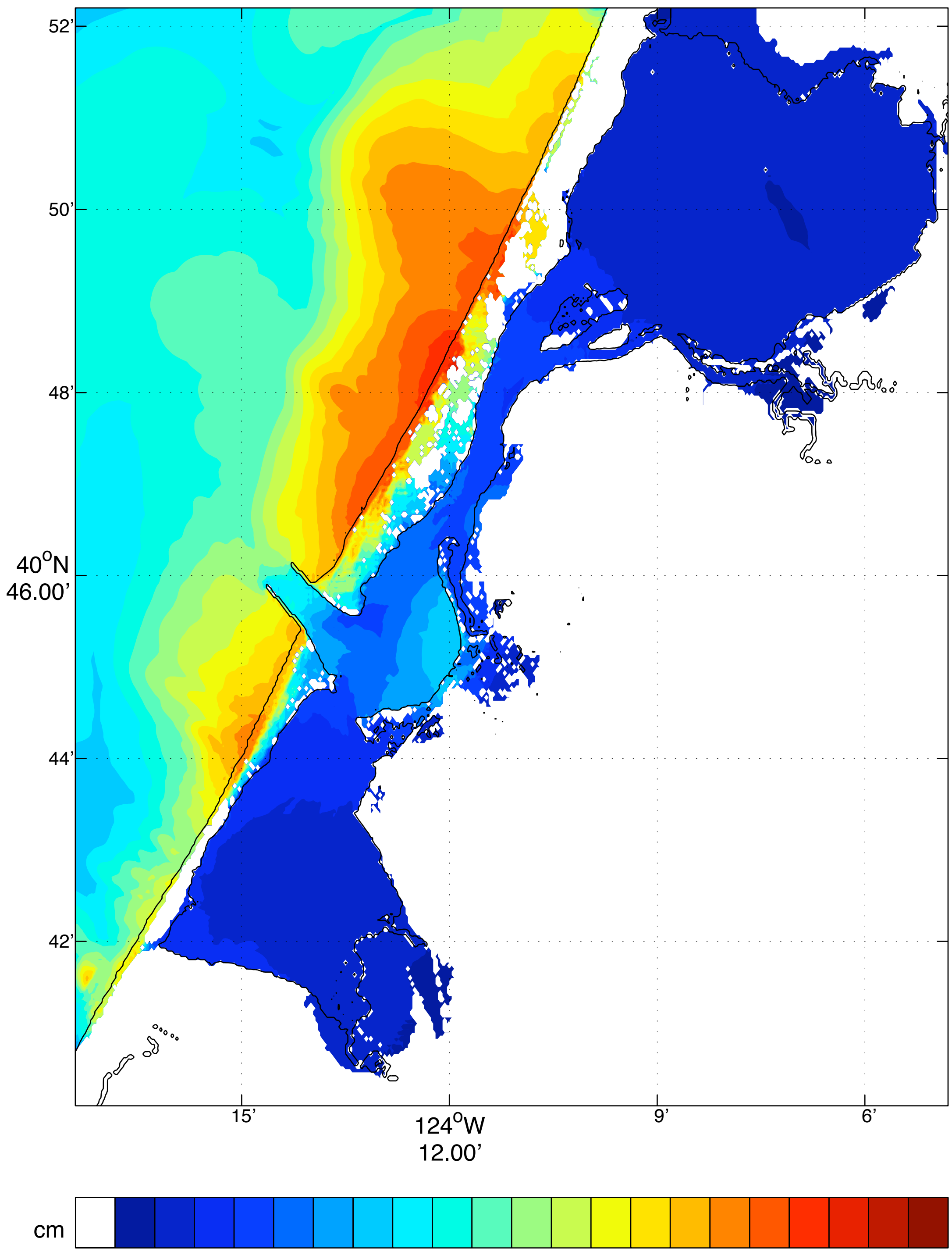

Figure 25 Map of the maximum wave height prediction from the Eureka forecast model for the KISZ05 Mw 9.3 synthetic event.